CRANFIELD UNIVERSITY

TAO LI

Digital Assembly Process Design for Aircraft Systems

SCHOOL OF ENGINEERING
Aircraft Design Programme

MSc by Research
Academic Year: 2011 - 2012

Supervisor: Dr. Helen Lockett
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ABSTRACT

The research described in this thesis concentrates on the development of an integrated assembly process design for aircraft systems.

Assembly process design is one of the most important and complicated activities in aircraft manufacturing. Many solutions are suggested in previous research to develop process design method. But gaps are found in assembly process design of aircraft system in following studies. In this research, an integration approach which combined with product development philosophy, design for assembly method and digital assembly technology is proposed to solve the issues in the whole product development lifecycle. Three case studies from different design phase are used to examine the integrated process design method.

The research results demonstrate that the proposed digital process design method can be used to develop manufacturing strategies of system assembly in early design phase, and improve the accuracy and operability of assembly instructions according to 3-D assembly process plans in detailed design phase. The product design also benefits from this method in terms of correcting design errors in the concurrent engineering process.

A proposed process planning system framework based on lightweight CAD is developed in this research. The customized assembly representation of 3DVIA system illustrates the advantages of lightweight CAD when applying in shop floor.

Keywords:

Aircraft system assembly, process design, assembly simulation, design for assembly, lightweight CAD, concurrent engineering, 3DVIA

ACKNOWLEDGEMENTS

I would like to express my sincere thanks to Dr. Helen Lockett, my supervisor. Thanks for her help, assistance and patients. Thanks also to Aviation Industry Corporation of China and China Scholarship Council for their supporting on my research at Cranfield University.

Thanks also to Dr. Shijun Guo for his help to obtain research material. Special thanks to my classmate Mr. Xiaoyang Wang for the support and advice on fuel system design.

Thanks all the people who encourage me to finish the research all the time.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF NOTATIONS

2-D: Two-dimensional

3-D: Three-dimensional

3DIF: 3D Industry Forum

AP: Assembly Planning

API: Application Program Interface

APU: Auxiliary Power Unit

AVD: Aerospace Vehicle Design

AVIC: Aviation Industry Corporation of China

BOM: Bill of Materials

CAD: Computer-Aided Design

CAE: Computer-Aided Engineering

CAM: Computer-Aided Manufacturing

CAPP: Computer-Aided Process Planning

CAQ: Computer-Aided Quality

CATIA: Computer Aided Three-dimensional Interactive Application

CGR: CATIA Graphical Representation

CRM: Customer Relationship Management

DCAC: Define and Control Airplane Configuration

DELMIA: Digital Enterprise Lean Manufacturing Interactive Application

DFA: Design for Assembly

DFM: Design for Manufacturing

DMU: Digital Mock-Up

EBOM: Engineering Bill of Materials

ECS: Environmental Control System

ERP: Enterprise Resource Planning

GDP: Group Design Project

GT: Group Technology

IPT: Integrated Product Team

IRP: Individual Research Project

MBOM: Manufacturing Bill of Materials

MES: Manufacturing Execution System

MP: Manufacturing Plan

MRM: Manufacturing Resource Management

NC: Numerical Control

OA: Office Automation

PBOM: Process Bill of Materials

PCB: Printed Circuit Board

PDM: Product Data Management

PLM: Product Lifecycle Management

RP: Resource Planning

SCM: Supply Chain Management

VBA: Visual Basic for Applications

VR: Virtual Reality

WWI: World War I

WWII: World War II

XML: Extensible Mark-up Language

1 Introduction

1.1 Background

The AVIC MSc training program, which is a cooperation program between Cranfield University and Aviation Industry Corporation of China (AVIC), started in 2008. Based on the first three years' successful Flying Crane group design project (GDP), the fourth cohort of AVIC students takes a new challenge to flying wing (FW-11) airliner in 2011.

Flying Crane, also known as AVIC-8 project is a 130-seat airliner, aiming primarily at China's domestic market. The new FW-11 project is a flying wing airliner with a typical 200 seats aiming the intercontinental airlines.

After five months' hard work on the FW-11 conceptual design, most of the AVIC students started their individual research project (IRP) based on the GDP design results or spreading to their related research field. However, due to different work background, some IRP topics are partly related to the conceptual design. The author's IRP topic is digital assembly process design for aircraft systems.

1.2 Digital Assembly Process Design for Aircraft Systems

The application of Computer Aided Engineering (CAE) has deeply influenced and changed the aircraft industry for quite a long time. One of the most important activities of process design is process planning. To improve the process planning performance and efficiency, aircraft industries developed Computer Aided Process Planning (CAPP) early in 1970's [1]. Although CAPP has been developed more than 40 years, a widely application in industry is in recent 15 years [2].

Since assembly is an all-important sector of manufacturing industry [3], which takes 50% to 60% of the labour in aircraft manufacturing [4]. Aircraft industry started to use digital manufacturing to reduce the cost. It is reported that one of Boeing's project named Define and Control Airplane Configuration /

Manufacturing Resource Management (DCAC/MRM) which put into practice in 1994, had shorten research cycle to 50%, reduced problems to 50% and diminished the cost to 75% [5][6].

Compared to aircraft parts manufacturing and structure assembly, system assembly is a more manual work. Because of more advanced functions are equipped to large advanced aircrafts like Airbus A380 and Boeing 787, usually, systems become more complicated which lead to difficulty for assembly process planning engineers to arrange assembly sequence. Besides, some issues are found in practical assembly due to the shortage of product representation in 2-D drawings. Thus, a development of computer aided assembly process design method is needed to reduce the heavy work of engineers, and make the representation more visible to assembly operators.

1.3 Project Aim and Objectives

1.3.1 Project Aim

The project aim is development of a process design method to represent aircraft system assembly process in 3-D way. There are three main research activities, which are to propose a process when doing assembly simulation process planning in detail design phase, to apply design for manufacture and assembly (DFMA) principle in design and propose process design in early product design phase, and to propose the framework of Assembly CAPP system when Digital Mock-Up (DMU) models are considered as the main or even only data source in manufacturing.

1.3.2 Research Objectives

The research work will be divided into a few stages as below.

a. Previous research field study

- Read technical and academic research books about CAD/CAM/CAPP, process planning, assembly design, modelling and Virtual Reality.

- Investigate existing simulation solutions and the application in design and manufacturing.
- Investigate how to analyse DMU models to obtain useful information for process design and what information should be included in the DMUs for manufacturing usage when building CAD models.

b. System assembly modelling and simulation study

- Learn to use CATIA to do the aircraft system modelling.
- Learn to use possible software to simulate the assembly process based on the detailed CATIA aircraft system models.

c. Propose, then apply the process and method

- Develop a process planning method to describe assembly process in 3-D way instead of using text documents.
- Detailed modelling and simulation
- Develop assembly process strategy for FW-11 in early design phase
- Investigate and illustrate how to use the proposed method to find out potential product design and process design problems.

d. Propose the integrated process planning system used in final assembly plant

- Investigate how CAPP links CAD and CAM, and the management of CAPP input and output when DMU models are considered as the main or even only data source in manufacturing.
- Investigate system requirements.
- Propose integrated system for final assembly plant.

e. Discussion and thesis writing up

1.4 Overview of Group Design Project

The author was involved in several groups in different design phases of FW-11 GDP during five months. In design phase I Derivation of Requirements, the author was in the geometric design characteristics team to comprehensive survey the geometric characteristics of existing 150 to 250 seat aircraft. Then, in the family issues and design constraints team, the author proposed some additional design constraints that need to be considered in the requirements. In design phase II and III (conventional baseline and flying wing approach), the author was in the cabin layout & family issues team. Finally, the author was in charge of the video produce for final presentation.

In the GDP work, the author mainly concentrated on cabin layout & family issues. As an end user of DASSAULT SYSTEMES CATIA data output, the author studied parts and assembly modelling first according to the 3-D cabin arrangement. Also, CATIA drafting tool is used to make some 2-D cabin drawings and section views. These CATIA modelling and drawing practice help the author to get familiar with Computer Aided Design (CAD) engineering process. More detailed GDP contributions refers to Appendix A.

1.5 Scope of the Research

Aircraft system assembly activities take place mostly in final assembly plant. Other closed related fields are assembly work in flight test and maintenance organization including the removal and installation of finished product and engine. Since assembly is a special activity which makes close relationship between product design and process design. Not only should the research concentrate on assembly process design, but also the product design in 3-D environment. Besides, it is difficult but crucial to take manufacturing and assembly into account as early as possible in the product design cycle [7]. Assembly strategies should be considered more according to DFMA method application.

The research described in this thesis is mainly relevant to aircraft industry although some ideas came from other similar industry like automotive industry, or more general field using assembly technology. Furthermore, both the design process and integrated application system developed in this research are based on the investigation of current aircraft manufacturing industry, especial the product development process of AVIC, but the proposed method is by no means limited to this situation.

1.6 Thesis Structure

The general introduction is given in chapter 1, which includes project background, brief content of GDP and IRP description. More GDP contributions will be found in appendix, since it is the basis of one case study.

As the general issues and project aim mentioned in chapter 1, it is necessary to examine different aspect concerning assembly activities and product development in aircraft industry. Relevant literature on the research topic including assembly technique, CAE process, DFMA and product data management (PDM) is investigated in chapter 2.

The investigation results from literature review, combined with the present assembly process design problems stated at the beginning of chapter 3, are used to formulate the research methodology. To develop the ideal process which can be used in the product development life cycle, this chapter therefore considers different research methodology for different product design stage and application field.

Chapter 4 presents the research case studies in accordance with the methodology discussed in chapter 3. The proposed integrated process planning system for final assembly plant is described in chapter 5. Finally, the thesis concludes with chapter 6.

1.7 Summary of Chapter

This chapter has outlined the project background which is based on the cooperation between Cranfield University and AVIC. The scope of the work has been defined as the assembly process design, in particular aircraft system assembly in 3-D environment.

The question stated in the general introduction is how to reduce the heavy work of process engineers, and make the assembly process representation more visible to assembly operators.

2 Literature Review

2.1 Introduction

“Today’s manufacturing industry is best characterized as dynamic, global and customer-driven” [8]. There are two visible tendencies of modern successful engineering business: first, shortening the manufacturing cycle to meet market demand; and second, shortening the product development cycle to meet market opportunity. After years of researching, aircraft industry began to integrate manufacturing philosophy, CAD method and IT technology to gain the success.

Three aspects which are assembly, CAD method for aircraft industry and Product Data Management will be introduced in the literature review.

2.2 Assembly

2.2.1 Definition of Assembly

“Assembly is the action of fitting together the component parts of a machine or other object” [9].While “Assembly process is a series of tasks putting together a set of components to produce an end product” [2]. Depending on the situation, the term ‘assembly’ may designate the assembly process or the end product. Assembly process planning is an activity of manufacturing engineering that translates product design data such as 2-D drawings, 3-D CAD data, criterions and existing process capability into detailed operation instructions to guide operators assemble a product. These instructions usually include the assembly tasks involved, the sequence of assembly task, facilities and tooling methods, etc.

Two features make assembly especially important in the product development life cycle. Firstly,” it is inherently integrative, bringing together parts and therefore bringing together the designers and builders of those parts” [10]. In additional, single parts do not present any function by themselves on the assumption that product is consider as a minimization unit which cannot be subdivided. Thus, “assembly is the moment when a product comes to life” [10].

2.2.2 Development of Assembly Technique

Although the assembly process is one of the most complicated engineering in industry, it is still possible for workers to finish the task, since human has the most intelligent control system – brain, and the most sophisticated tool – hands. As mentioned before, manufacture business seeks the maximum benefits through the development. Pure manual assembly will lead to high labour cost and low efficiency which does not fit some industry with large production quantity. To examine possible method adapted for this research, it is necessary to investigate the development of assembly technique first.

The table below lists a brief development of assembly techniques in terms of period, symbol, characteristic and typical application field.

Table 2-1 Development of Assembly Techniques [3]

Period	before the 20th century	early in the 20th century (WWI)	around 1940s’ (WWII)	up to 1990s’	until now
Symbol	assemble manually	separate parts manufacturing and assembly	assembly line	automated assembly	integrated manufacturing
Characteristic	long time training, long delivery time, simple assembly produce	interchangeable components make mass-assemble possible	a team workers assemble the product together, every small part for each person	development of robots, robots production line, development of DFMA	lean manufacturing, CAD/CAM, programming robots, IT technology
Typical Field	all products	armament industry	Henry Ford, armament industry	electronics industry	PC industry, etc

It is clear from the table that assembly techniques are developing to meet the increase of production quantity requirement. Therefore, assembly approaches are developed to fit different industries. What is more, it is presented in some papers [11] that there are different assembly principles which are manual assembly, semi automation, flexible automation and fixed automation.

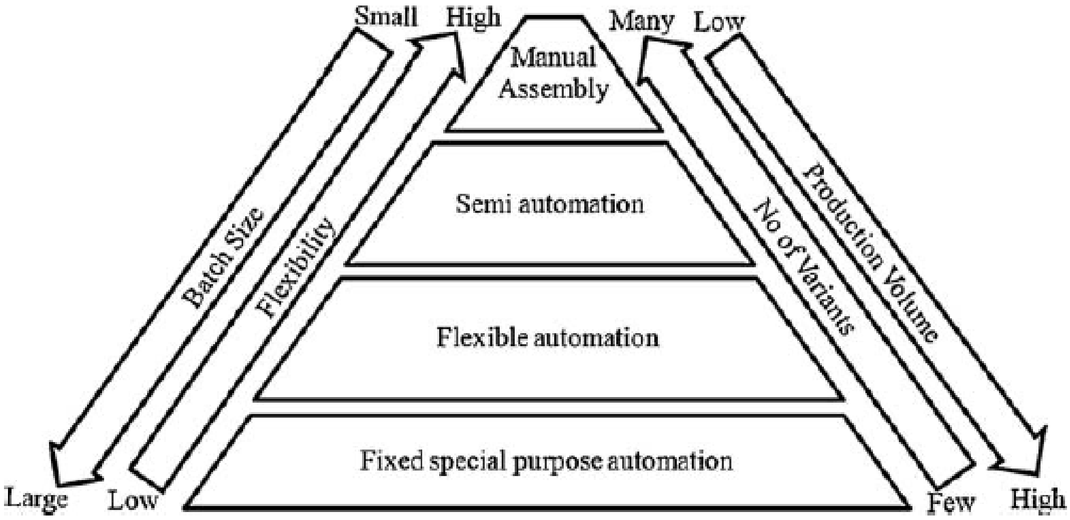


Figure 2-1 Performance Characteristics of Assembly Systems Following Different Assembly Principles [11]

The figure above shows the different assembly principles and their respective performance. As the typical application field mentioned in the table before, the electronics and PC industry produce enormous number of product every year, which belong to fixed automation and flexible automation. In particular, the usage of industrial robot is suitable for automatic parts manufacturing like Numerical Control (NC) machining. For assembly task, automated assembly is used for high quantity and simply assembly cases such as subassembly and printed circuit board (PCB) parts assembly. By contrast, industry with less production volume like automotive industry is in the semi automation level since some assembly tasks are still done by hand. The situation of aircraft industry is the same as automotive industry in some extent.

2.2.3 Aircraft System Assembly

A modern aircraft of large dimensions generally have typical systems such as hydraulic system, electric power system, fuel system, auxiliary power unit (APU) system, environmental control system (ECS), flight control system and avionics system. The figure below shows the real installation environment of different aircraft systems.

Figure 2-2 A Brief View of Systems in Boeing 737-600 [12]

Numerous of pipes, cable harnesses and finished products from these systems make the high complexity of aircraft system layout in product design. As the next step of traditional product development, process design inherits the complexity which leads to difficulty of assembly process planning.

Although the latest digital assembly technologies like robot assembly and digital measurement method are applied in aircraft assembly, it is mostly used in aircraft structure parts assembly. Little usage of robot was found in system ground subassembly instead of onboard.

It is also noticed by the research that the effort of aircraft system integration reduce assembly difficult in some extent. Systems parts especial finished products became miniaturized making the number of system parts smaller. However, even the latest A380 superjumbo airliner fully equipped with the latest design and manufacturing technology still face threaten from system assembly. It is reported that A380 production was delayed in 2006 due to electrical cable harnesses for the fore and rear fuselage could not keep up with the rest of the aircraft and did not fit when they came to be installed [13][14]. To fix the problem, some structure frames and cable harnesses need to redesign.

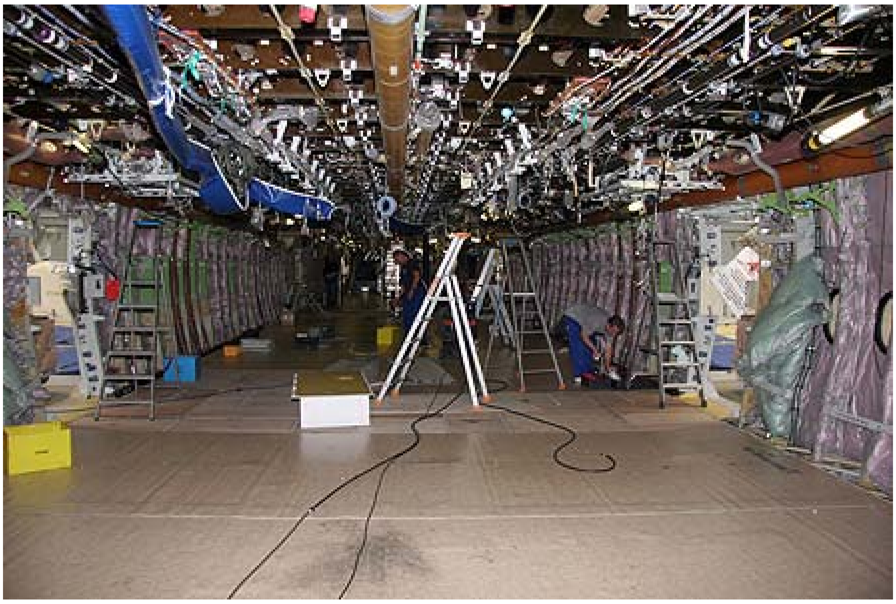


Figure 2-3 A380 Cable Harnesses Replacement [15]

Further analysis shows the problem is caused by many factors including wiring design problem, loose configuration control and software compatible issue. In spite of these factors, what should be emphasized is the high complexity of modern aircraft system contributes to the design difficulty.

2.2.4 Classification of Aircraft System Assembly Activities

Many aircraft system assembly activities are taken place in the final assembly plant. Although what exact assembly activities are used in manufacturing depend on different factory capability and detailed work breakdown structure, generally, system assembly activities can be classified as below:

Table 2-2 Classification of System Assembly Activities by Different Criteria

Criteria	Content
By assembly action	Location, layout, drilling ,riveting, gumming, jointing, connection, package , fasten, adjustment, inspection
By assembly object	Parts: such as pipes, tubes, cable harnesses, supports, etc.
	Finished products
	Standard parts: such as standard bolts, screws, nuts, washers, etc.
	Materials: such as primer, glue, cleaning fluids, lock wire, etc.

Other activities in the manufacturing flow also contain system assembly especially when problems are detected or maintenance requires. The table below lists the related fields and typical actions.

Table 2-3 Other Activities Relevant to System Assembly

Field	Typical action
System experiment	Air tightness: reinstallation of pipes, valves, finished products
	Energization test: reinstallation of cable harnesses, finished products
	System performance test: reinstallation of pipes, valves, finished products
Alignment	Reinstallation of finished products, supports
Test Flight Maintenance	Reinstallation of engines, equipments, pipes; Connection of plugs

2.3 CAD Method for Aircraft Industry

2.3.1 CAD Tools Used in Aircraft Industry

Computer Aided Design is now widely used to support aircraft design activities, and a digital mock-up (DMU) is produced as the master model of an aircraft design. The solid models designed in CAD tools represent accurate product geometry and installation position in 3-D environment. The high cost and low efficiency traditional physical mock-ups are less required, since DMU provides the opportunity to integrate and verify the product design.

The widely used Dassault Systemes CATIA V5 is an integrated Computer Aided Engineering tool which incorporates CAD, CAM, CAM and other applications. It is based on variational and parametric technology with user friendly graphical interface. CATIA can be used significantly improved the ability to complete the design to manufacture processes of very advanced structures. Boeing 777 airliner project and Lockheed Martin JSF project are typical successful applications of CATIA.

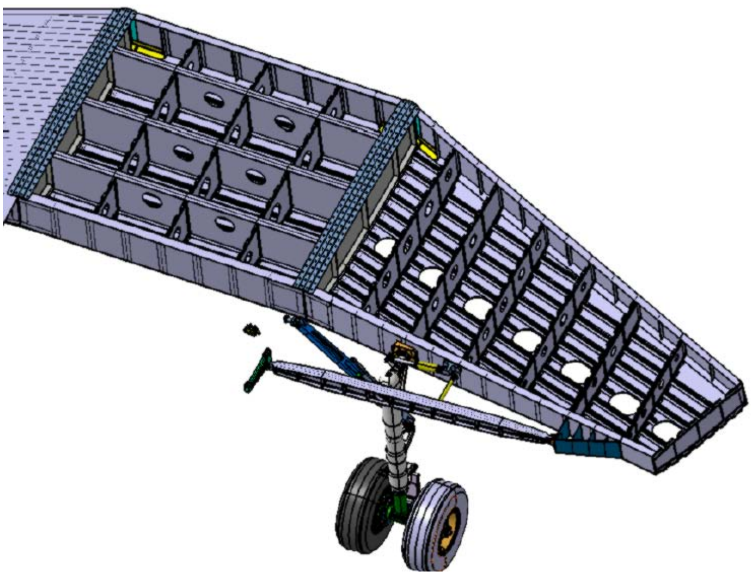


Figure 2-4 Flying Crane Digital Mock-up [16]

The assembly design application of CATIA allows creating a product model from a number of separate parts. These parts in this product assembly are not fixed together in physical but in logical. CATIA also provides tools for system geometry design. Aircraft system pipes (tubes) and cable harnesses assembly can be designed in CATIA Piping (Tubing) and Electrical 3D design workbenches.

2.3.2 Lightweight CAD Data

“The aim of lightweight representations is to support users at different stages of the product lifecycle in rapidly browsing, retrieving and manipulating product information” [17]. There are the advantages of this CAD format compared to raw CAD data:

- Lightweight CAD data has smaller document file size which is feasible for rapid CAD data sharing, especially on Internet.

- Lightweight CAD data cut down the modelling process data and simplify the geometrical representation to meet low computer hardware requirement, thus reduce the computer hardware cost.

- In collaborative situation, raw CAD data would leak commercial secret to the partners since in most cases they only need shape data of product.

- Departments such as process design and QC, they do not design the product but get information from the CAD data. Using lightweight CAD data will reduce the CAD software license cost.

In aircraft industry, CAD software like CATIA and UG are widely used. The typical detailed CAD data file size of a large aircraft would be at least several dozen Giga Byte. What is more, unlike the parts process planning use single CAD part model one time, the system assembly process design need to consider structures and systems together. When these CAD data are imported together, the software running would be very slow or even crash which leads to significant efficiency reduction. Lightweight CAD is a good solution of this issue.

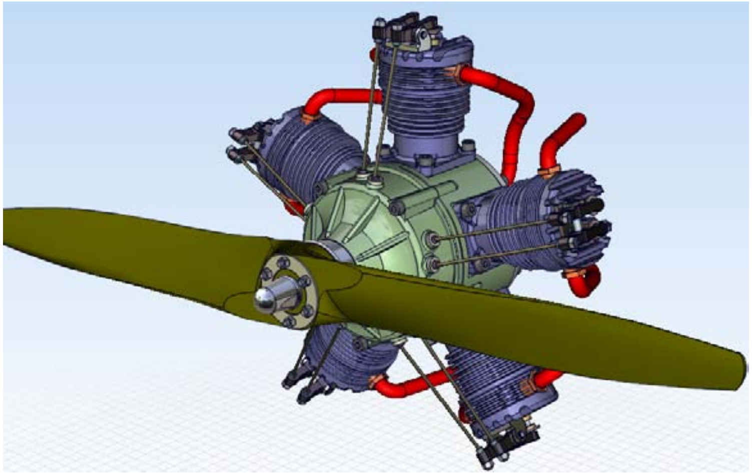


Figure 2-5 Lightweight CAD Data Representation

Many lightweight CAD data are developed to support Product Lifecycle Management (PLM). The table below shows a summary of different formats.

Table 2-4 Summary of Lightweight CAD Data Formats [17]

	Compression method	Developer	Supporting tools	Applications	Characteristics
U3D	Domain specific Node/Resource mechanism	Intel and the 3D Industry Forum (3DIF)	Adobe Acrobat Version 7.0 Open source	Sales & marketing Customer support Online promotions Maintenance Training	Level-of-detail Progressive streaming Rigid-body & skeleton-based animation File format and run-time extensibility
X3D	Domain-specific Type-specific field Fast InfoSet	Web3D Consortium	X3D Tools and Applications	Technical publishing Maintenance manuals, Websites, Database applications, Visual simulations Navigation systems	No heavy browser XML-based open profile/ components -based architecture Integration of advanced 3D techniques
3D XML	3D graphics compaction algorithm Reference/instance mechanism	Dassault Systemes/ IBM	V5R15, CATIA, Delmia, Enovia, Novia, Spatial, SmartTeam, SolidWorks, Virtools Dev 3.5 3D XML Player	Technical documentation Maintenance manuals Marketing brochures Websites Email	Level-of-Detail Multi-file architecture Easy to adopt Extensibility
JT Format	Lossless compression algorithm Domain-specific	Engineering Animation, Inc./ UGS Inc	JT Open Toolkit JT2Go	Lightweight visualisation format for PLM CAD-neural exchanging format Consistent 3D visualisation	Neutral exchange format Support of multiple files
PLM XML	References to external files	UGS Inc	UGS applications Open XML schemas	Connection UGS PLM Solutions products and third party adopter applications	Incorporation of product, part and process information Open source Support of multiple representations for shape definition Extensibility

It can be seen from the table that applications of lightweight formats cover many different industries. However, it should be argued that not all these formats can be used in product development phase because “some compression methods adopted are approximate or simplified geometric representations with domain-specific compression, while the compressed information or domains are out of the control of users” [17]. Actually, even some Lightweight CAD formats which announce to support PLM such as JT Format and PLM XML meet problems of low effectiveness when used in PLM. Thus, lightweight CAD can be used limited in late product development phase especially fields with fewer requirements for geometry modification such as technical publication and training. Song and Chung [38][39] propose an XML CAD system integrated in PDM. Ding, Davies and McMahon [40] also propose a new product representation approach using lightweight CAD to allow the association of product data through the product life cycle.

Further investigation found Dassault Systemes launched a new brand 3DVIA Composer based on Lightweight XML (Extensible Mark-up Language) format using in 3-D product representation in 2007. This type of format allows user to determine whether import CATIA graphic data or not.

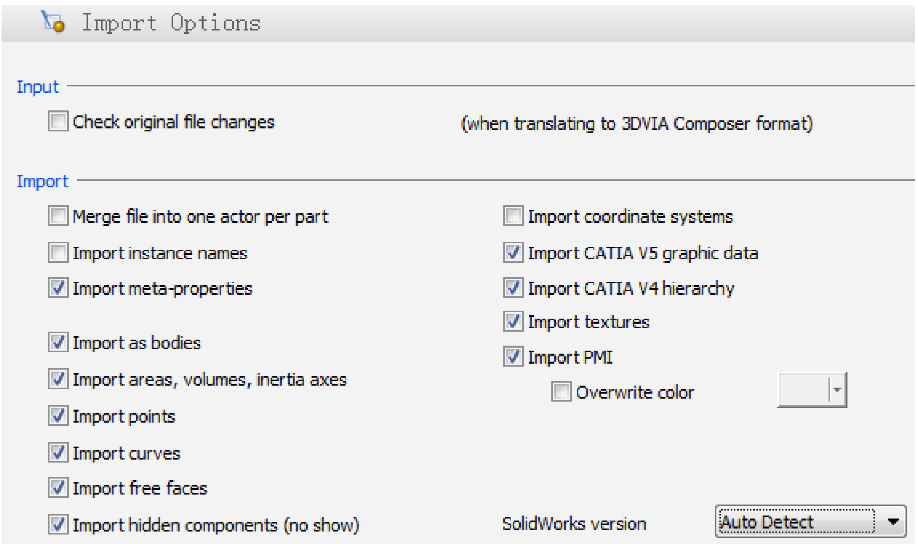


Figure 2-6 3DVIA Composer Import Options

What is more, 3DVIA Composer can be integrated into PLM system such as Agile, SmarTeam, ENOVIA, and many others [18]. Official example shows CATIA and 3DVIA Composer content is not only managed within PLM system, but also demonstrates that as the CATIA data is modified into a new release, the 3DVIA Composer content is automatically updated by PLM system.

2.3.3 Computer Aided Process Planning

In traditional point of view, process planning is regarded as a manual operation, usually carried out by qualified and experienced engineers [1]. The accurate rate of process planning mainly depends on the engineer's personal experience and his knowledge of manufacturing process, facilities, materials and methods. Thus, different engineers with different levels finish a process plan in various approaches. Computer technology was introduced to optimize these approaches and try to find the best one.

Since the idea was first introduced by Niebel in 1965, the research of CAPP developed greatly. In the following years, many types of CAPP system was developed, such as retrieving, variant, generative, comprehensive, expert, tooling system, etc [19].

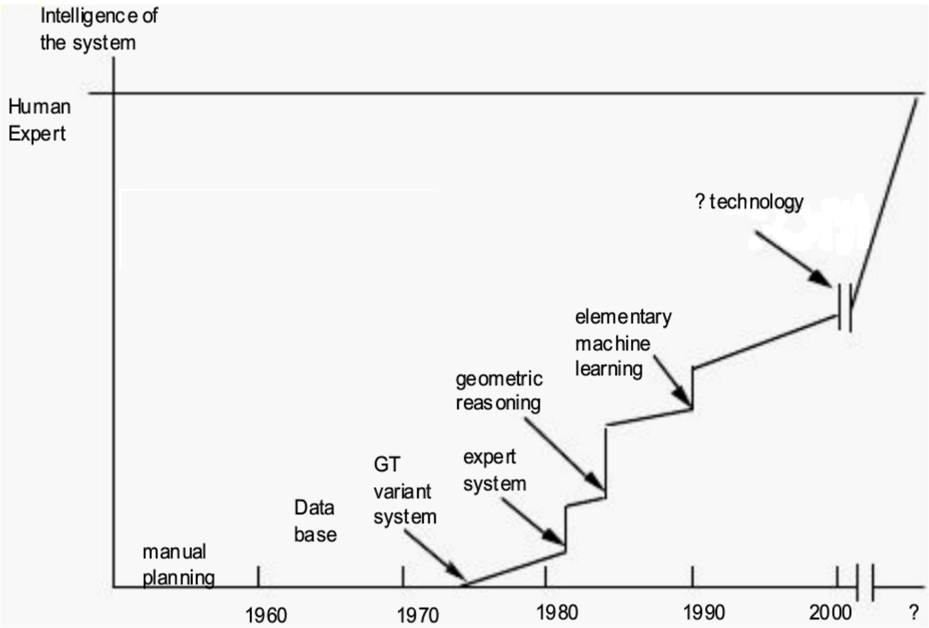


Figure 2-7 Development of CAPP System

One of the most famous is CAM-I's Automated Process Planning system which developed in 1976 [20].

The initial purpose of developing CAPP is to develop an automatic system to replace the work of process planners which concentrating on intelligent automation, instead of an assistant system. But because of the personalization and complication characteristic of process design, it is impractical that CAPP completely replace process planners' work. Automatic CAPP system can be only used in certain industry, even certain parts like rotational and Box-Type parts. Thus, an assistant system is widely accepted in industry which aims to help engineers to improve the efficiency and standardization of process design.

Few literatures are found in CAPP of assembly. Eversheim and Scheewind [21] noted a need exists to develop CAPP with assembly activities. Their research result had realized assembly function should be integrated in CAPP instead of machining. Delchambre [3] discussed computer aided assembly planning in his book about automatic approaches. However, Sarma and Wright [22] noted according to their research, that there have been many attempts to automate process planning, but successes are limited. Guan [23] recognised in his research that assembly process planning based on 2-D drawings requiring much time to complete the task. Jasthi et al. [24] investigated four types of process planning, which are text-based, graphical simulation, pictorial process and numerically controlled programme process planning. He indicated graphical simulation process plans provide collision check, process visualisation and process sequencing, therefore this type are more helpful to both process planners and workers. The benefits of assembly process planning using simulation pre-planning have been evaluated by Arnold and Ramulu [31]. They conclude that an average of 29.6% time saving is made by applying assembly simulations as a process planning aid.

2.3.4 Concurrent Engineering

Traditional product development uses serial design and manufacturing process.

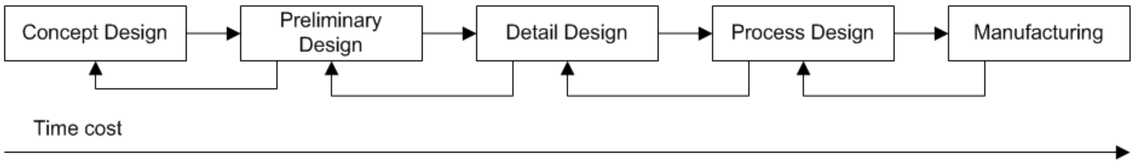


Figure 2-8 Serial Product Design Model

There are some characteristics in serial design model:

- Base on serial process. The next stage begins when the former stage is finished
- Difficulty in data exchange among different design systems.
- Increasing cost by frequent product changes.
- Long design time which does not fit market requirement.

In aircraft industry, due to the shortage of computer technology support in 1950s', prototypes or detailed full scale mock-ups had to be made first to develop the product. This traditional process meets many difficulties such as high cost of product change, low efficiency of concurrence and low flexibility of family product development.

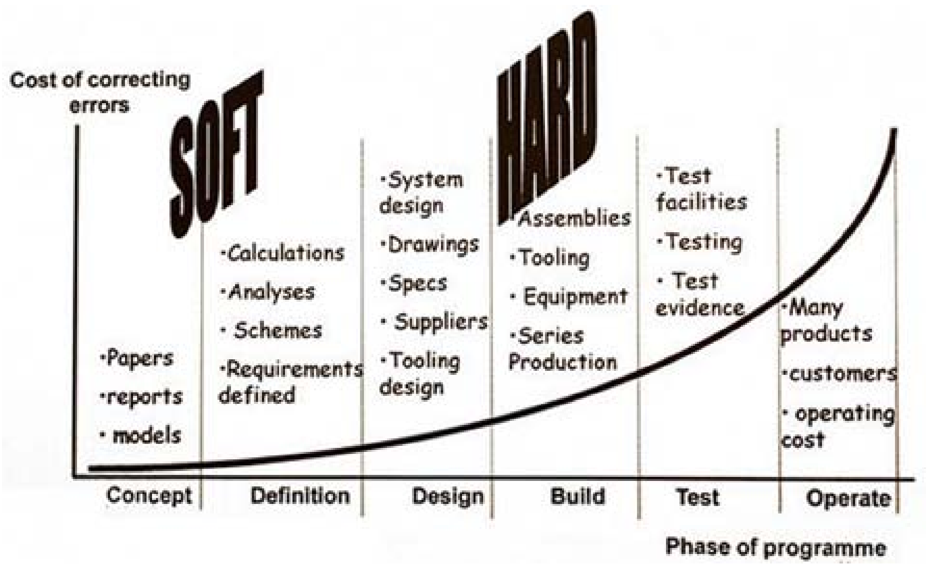


Figure 2-9 Cost of Correcting Errors in the Life Cycle [25]

This figure illustrates the cost of correcting errors in the aircraft develop life cycle. Before the build phase, the cost of correcting errors keeps at a low level. When it comes to build and test phase, the cost climbs significantly compared to the former three phases. It is obvious from the curve that the cost would be enormous if correcting errors after the product's release.

To meet the rapid growing market requirement and reduce the high product change cost, concurrent engineering was applied in many companies since 1990s'. In 1991 the Concurrent Engineering Forum that took place at Cranfield University defined concurrent engineering as "the delivery of better, cheaper, faster products to market by a lean way of working using multi-discipline teams, right first time methods and parallel processing activities to continuously consider all constraints" [10].

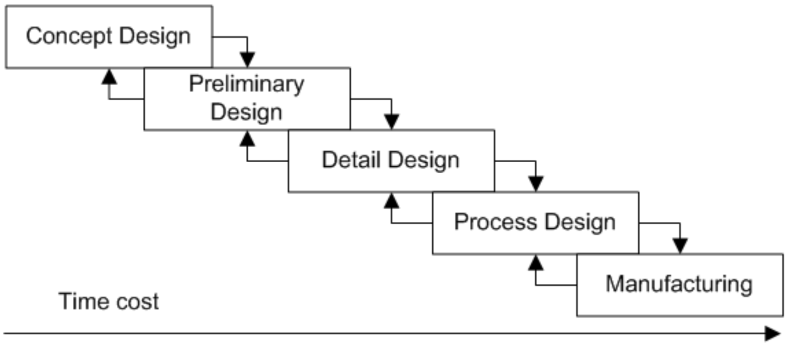


Figure 2-10 Concurrent Product Design Model

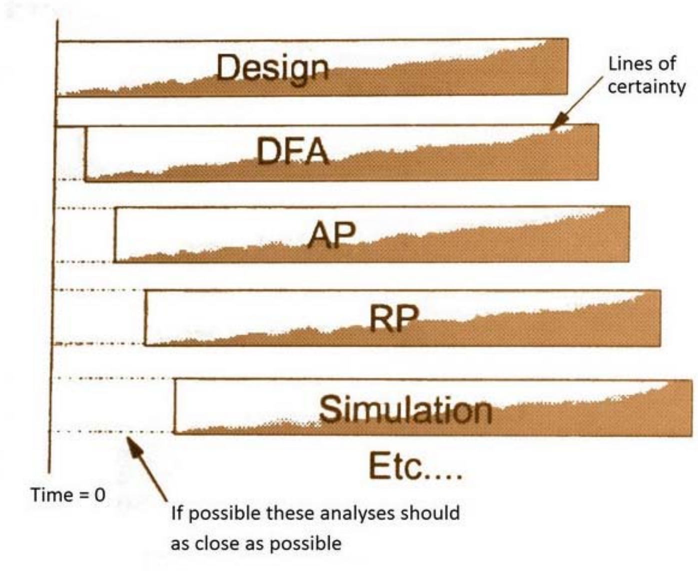
2.3.5 Design for Manufacture and Assembly

Boothroyd and Dewhurst state in their book that DFMA combines two meanings. "DFM means the design for ease of manufacture of the collection of parts that will form the product after assembly, while DFA means the design of the product for ease of assembly" [7]. This design method encourages concurrent engineering during product design so that the product qualities involve with both designers and other developing members with their concern. DFMA has been proven to be a saving tool as used by many aircraft companies. Report shows a cost saving of $86,000 per aircraft in MD-11 cargo liner development, and a cost saving of $4,000 per aircraft in MD-11 #2 Bulkhead [26].

When developing a product, the maximum potential cannot be achieved without considering all phases of product development life cycle. DFMA meets the requirement by proposing key assembly factors before the product goes on to manufacturing stage. These key factors include product appearance, type, the number of parts required, and required assembly motions and processes [26].

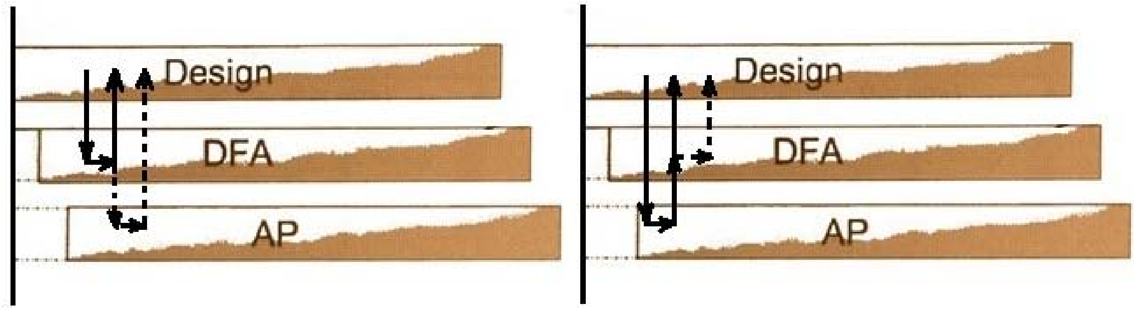
For assembly design, Boothroyd and Dewhurst encourage DFA should be considered at all stages of design process, but especially the early stages. The DFMA book authors also recognise the issue of how to integrate the DFA analysis early enough in the design process to have the most benefit. However, no specific methods are given from the book about the implementation of DFA in conceptual design phase. In Simpson's research [27], he recognises that Boothroyd and Dewhurst's DFA principles are more suitable for existing designs and applying in detail design phase although they strongly suggest users to apply DFA in conceptual design. To solve the problem, abstract DFA principles approach are proposed for conceptual design in Simpson's research.

Fan and Wallace [28] recognise the growing information certainty with the design process going. The figure below shows that as the design progresses and parts of the design become fixed and the level of uncertainty in the design decreases, more of this information can be extracted from the product model.



DFA = Design for Assembly, AP = Assembly Planning, RP = Resource Planning

Figure 2-11 Information Certainty Grows with Design [28]



DFA = Design for Assembly, AP = Assembly

Figure 2-12Flexibility of Iterate Method Used in Concurrent Engineering [28]

The iterate method used in concurrent engineering is illustrated in the figure above. This design philosophy combined with the abstract DFA principles answers the application problems of DFA in very early design phase.

2.3.6 Product and Manufacturing Information

Product and Manufacturing Information (PMI) describes non-geometric attributes of product necessary for manufacturing usage [29]. In traditional 2-D drawings, PMI refers to tolerance, welds types, surface finish, datum target, annotations, etc. While in 3-D product representation environment, PMI may not only includes the attributes listed before, but also contains geometric dimensions, Bill of Materials (BOM) and 3-D functional textual instructions. For aircraft systems, PMI can be installation and experiment notations.

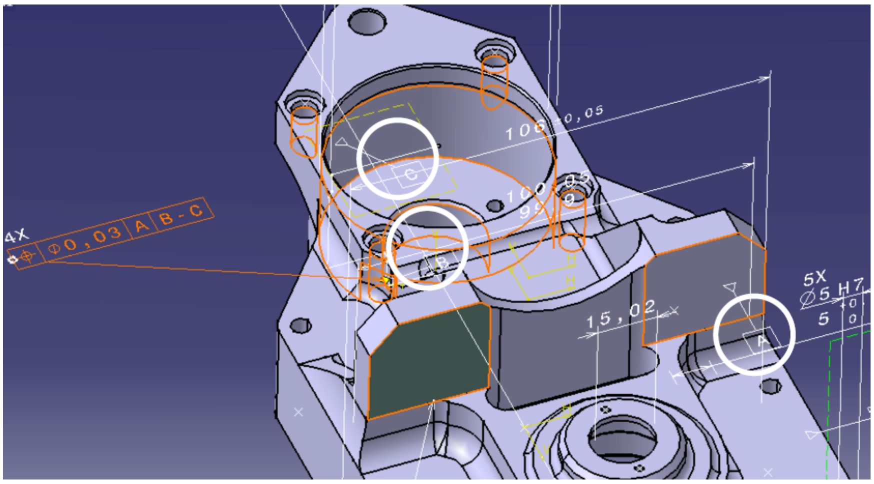


Figure 2-13 PMI in CATIA 3-D Environment [29]

In 3-D CAD system like CATIA, 3-D textual annotation can be directly exported into neutral CAD system formats such as JT and STEP. Thus, PMI can be inherited to down-stream CAD/CAM systems. NC programming software can directly access PMIs from 3-D CAD data if permissions are obtained from modelling. Investigation shows 3-D PMIs are also used in tolerance analysis and digital measuring systems.

2.4 Product Data Management

2.4.1 PDM System in Aircraft Industry

Product Data Management (PDM) system is a database system that manages all the production related data from different departments, including design, manufacturing, purchasing, QC, marketing through the product life cycle [30].

Some key features of PDM are vital to aircraft industry:

- Product information storage and retrieval.
- Task, configuration and change management.
- User role control.

Large aircraft is made of thousands of individual parts, tens of thousands of standardized components and hundreds of finished products. In the product development flow, numerous of product data are produced. These data, including 2-D drawings, 3-D CAD models, process planning documents, QC plans, production plans, tooling information and parts in stock are all needed to be stored in groups and indexed. Users with different concerns can easily retrieve they need from the database through PDM system.

PDM system is also used in task and configuration control. With this function chief engineer or product manager can supervise their group members' work state, and achieve the stage-gate goals. Besides, since products like cars and airplanes often aim different market area. Usually, “the hierarchical Bill of Materials (BOM) is the main product structure used in PDM systems” [30].

According to flexible BOM configuration, new product can be fast developed to meet the fast market change requirement.

2.4.2 Integration of PDM System

The figure below is a typical PDM system integrated with 3-D product data browse.

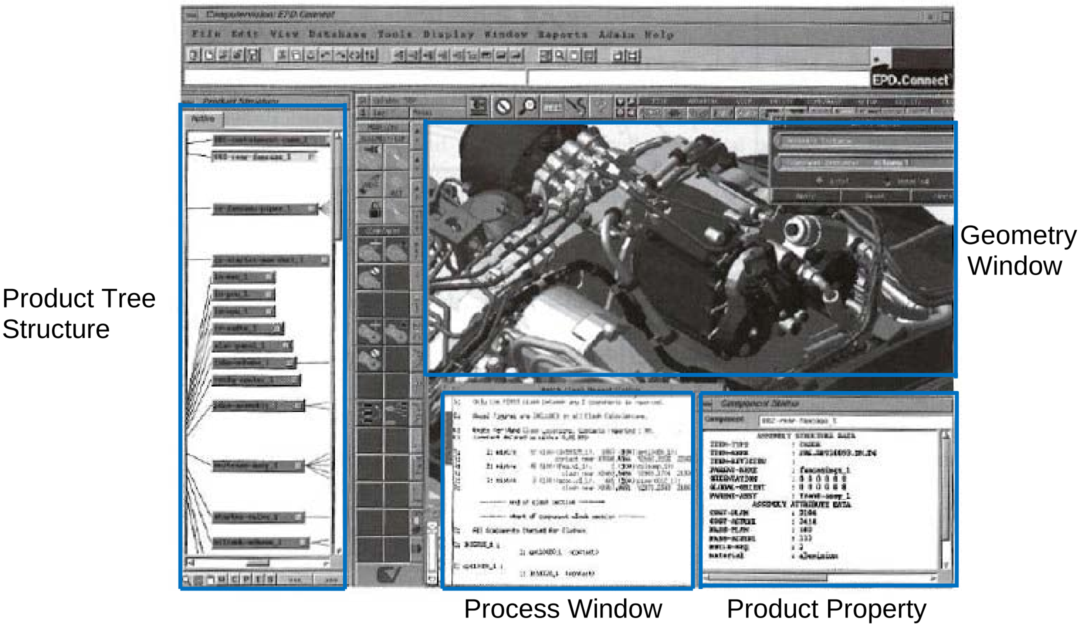


Figure 2-14 Screenshot of a PDM System [30]

PDM systems usually allow the integration of various product related data structures into a uniform framework, which include geometric modelling, process planning, engineering analysis and engineering data management. Famous PDM system such as Dassault Systems Enovia, PTC Windchill and UGS TeamCenter provide high integration of CAD data. For instance, CAD files like 3-D models and 2-D drawings are managed as CAD documents in PTC Windchill system. CAD documents and their product structures can be associated to Windchill parts. In this system environment, A CAD document is the product designer's view of the product, and a Windchill part is the rest of the product development members' view of the same product. Some manufacturing information is only associated with the corresponding Windchill part. This associative relationship enables CAD structures to automatically build part structures in Windchill. Thus, this top-down design allows process design information based Windchill part structures to build CAD structures [32].

2.5 Summary of Chapter

This chapter reviews three aspects of assembly, CAD method for aircraft industry and Product Data Management, which are relevant to the research topic. Some recent developments in these fields have been investigated and the complexity of aircraft system assembly engineering also has been noted. Since the thesis concentrates on aircraft system assembly, attention has been drawn to the CAD method used in assembly. For the same reason, PDM, which is widely used as a management of assembly process planning results in aircraft industry, has been described in detail.

The product design in CAD systems is reviewed as part of the research basis. Aircraft assembly process planning is found to be a difficult and complex task. Not only is it very subjective but also experience driven. The research also recognises the potential of lightweight CAD data used in Product Lifecycle Management.

A weakness of DFMA principles applied in conceptual design is that this method is too quantitative to use in very early design phase. New approach is proposed by transforming Boothroyd and Dewhurst's original specific DFA principles into abstract DFA guidelines.

This chapter concluded with the investigations of aircraft assembly related fields. 3-D CAD system tools, combined with integrated CAD method are considered as the basis of 3-D assembly process design. The process design results are then managed in PDM system.

3 Development of Research Methodology

3.1 Introduction

This chapter will formulate the research methodology based on the results of the literature review discussed in chapter 2 and further investigation of current assembly process design. Thus, a deep investigation will be introduced first. Then the next part is research methodologies in different design phase, and followed by the methodology used for development of assembly process planning system.

3.2 Investigation of the Current Assembly Process Design

3.2.1 Process Design Flow and Framework

In spite of different technology and marketing strategy, product development can be generally divided into product design, process design and service design. The figure below illustrates product development activities after product data release from detail design phase.

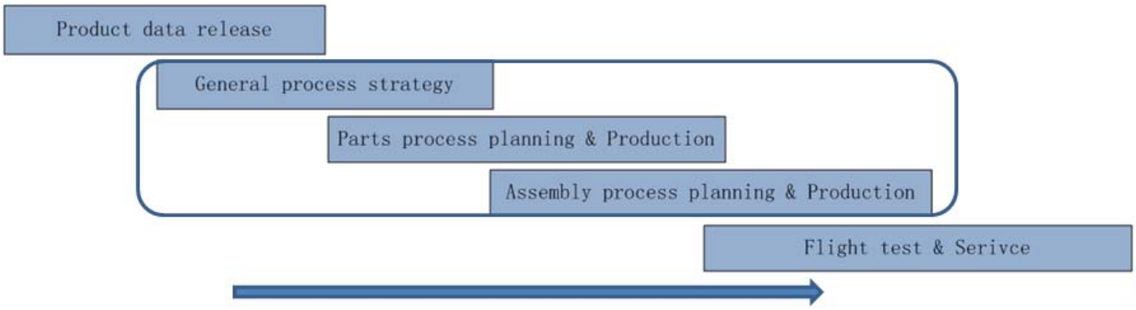


Figure 3-1 Activities after Product Data Release

All these steps are in the concurrent engineering process. The following three steps in the frame belong to manufacturing stage, where process design is mainly taken place.

To propose a process for system assembly design in 3-D environment, it is necessary to investigate the present drawbacks first. Since the research is part of the cooperation between AVIC and Cranfield University, the situation in AVIC should be investigated in particular.

The figure below is the typical process design systems frame in AVIC.

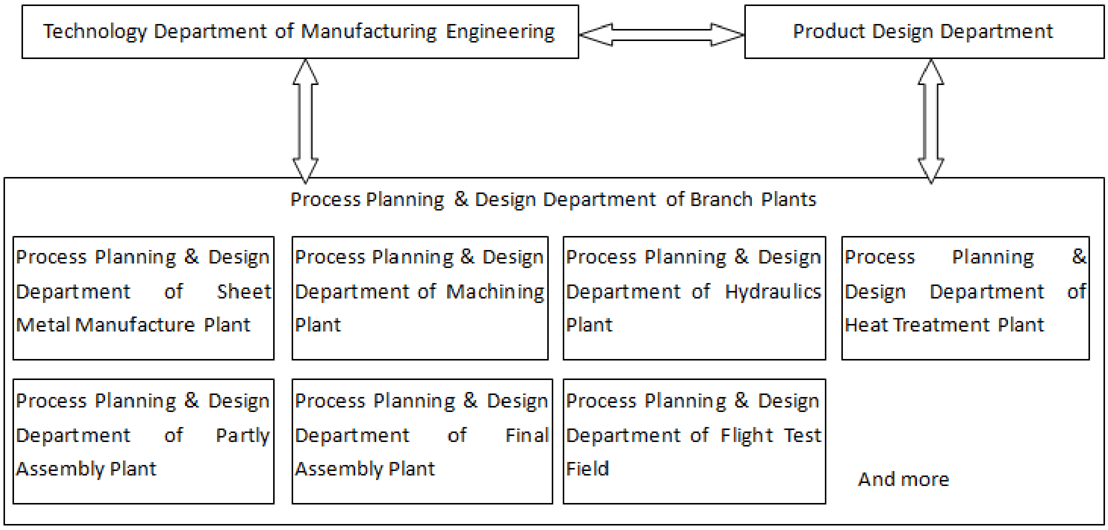


Figure 3-2 Process design system frame in AVIC

The main responsibilities of these departments are:

- Product Design Department
  a. Research and development of aircrafts.
  b. Produce product design data for manufacturing usage.
  c. To help solving technical problems with manufacturing departments.
  d. Produce maintenance instructions to product users.
- Technology Department of Manufacturing Engineering
  a. Collaborating with product design and plant's process design department, basing on the current manufacturing capacity, to subdivide aircraft into units for assembly.
  b. To convert the Engineering Bill of Materials (EBOM) to Process Bill of Materials (PBOM) to represent the process separation surface and manufacturing route.
  c. To decide the general processing strategy of parts manufacturing, assembly and flight test.

   d. To deal with technical problems with product design and plant's process design department.
   e. To constitute technology standards.

- Process Planning & Design Department of Branch Plants

  a. Following the process separation surface and general processing strategy, to design the manufacturing process in detail.
  b. To produce manufacturing shop floor instructions and other temporary technical documentations.
  c. To convert the Process Bill of Materials (PBOM) to Manufacturing Bill of Materials (MBOM) to reflect the manufacturing structure, and to support ERP (Enterprise Resource Planning) and MES (Manufacturing Execution System).
  d. Collaborating with Technology Department of Manufacturing Engineering, to present tooling requirement in detail to tooling design department.
  e. To deal with technical problems in shop floor production.

In this frame, process departments in shop floor level decide detailed process planning and solve practical production problems. On the other hand, process departments in higher level focus on general process design strategies.

3.2.2 Present Process Planning Method

An assembly process plan provides task related information gathered in instructions for workers in shop floor to accomplish the assembly or experiment. Generally, an assembly plan consists of work operations, notes, process drawings, components and configuration control parts. The work operations which consume much of process engineers' time are considered as the most important part of an assembly process plan. Some important activities should be taken by process engineers in order to accomplish work operations. These typical activities are listed below:

- Determine the location and location tolerance of each part. Verify the manufacturing capacity to meet task requirement.
- Arrange the assembly sequence.

- Determine whether equipments and tooling are used in the task.
- Verify the accessibility of the process.
- Incorporate typical process requirements and special assembly notes into the process plan.
- Incorporate Quality Control (QC) inspection requirements into the process plan.

Since product development engineering is a top-down process, the research should concern the integration of product design and process design. Hence, the inputs of assembly process planning should be introduced particularly.

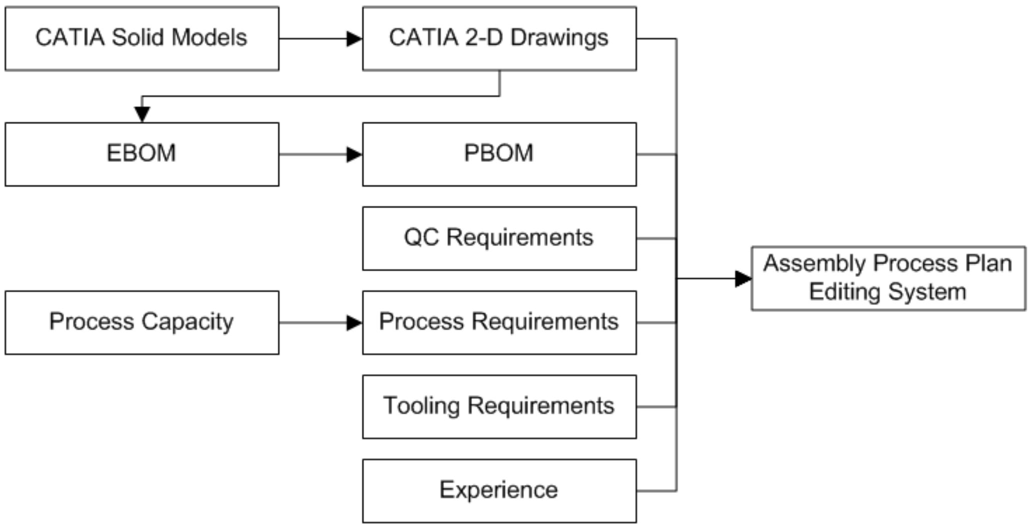


Figure 3-3 Input of 2-D Assembly Process Planning

What should be noticed through the figure above is, in traditional product development process, process plans are based on 2-D drawings instead of 3-D solid models. The possible reason is these CATIA solid models are modelled for 2-D drawings only. What is more, these models are not real DMUs. Most of the system models are designed isolated without integrated clash check. Different system models do not get together to make detailed collision detection and accessibility verification in product design stage.

The process planning method used in final assembly plant is described as:

- Mainly based on engineers' personal work experience to analyze 2-D drawings.
- Following some technology standards.
- Write the assembly process in textual format.
- Reflect tooling requirement by text-based description and 2-D drafts.

A brief assembly process planning flow in the final assembly plant is illustrated as below:

Step 1: Design the assembly process node structure by a chief process engineer.

Step 2: According to the assembly process node and certain criteria, divide 2-D product drawings into many parts, and then do the process planning. These subdivided criteria usually include system operation principle, assembly work breakdown structure, system test requirements and inspection requirements.

According to the work breakdown structure or sub contract requirement, a supposed assembly process nodes definition in final assembly plant is divided into four levels:

Table 3-1 A Supposed Assembly Process Nodes Definition

Level	Definition	Content	Main Work
4	Installation	System installation	Finished product, cable harness (wiring), duct installation
3	Joint	Big parts joint	Wing Joint, landing gears, engine, empennage installation and related parts installation
2	Test	System test	Air tightness test, energization test, system performance test, alignment
1	Delivery	Aux inspection & Installation	Cover installation, final Inspections

Then, process planners expand the assembly process node structure by placing individual work content in the form of work instruction numbers in these nodes. Therefore, the manufacturing process is represented in a reversed tree structure to support the production requirement.

Step 3: Produce manufacturing shop floor instructions.

In conclusion, the inputs of assembly process planning activity are product information, manufacturing capability, technology standards. And the outputs are operation instructions, facility required, parts required and material required. A text-based assembly planning sample is illustrated in Appendix B.

3.2.3 Application of Present Method

The following example illustrates the application of present system assembly. The figure below shows a CATIA 2-D drawing of fuel sub-system. Process planning activates are taken following the method mentioned before.

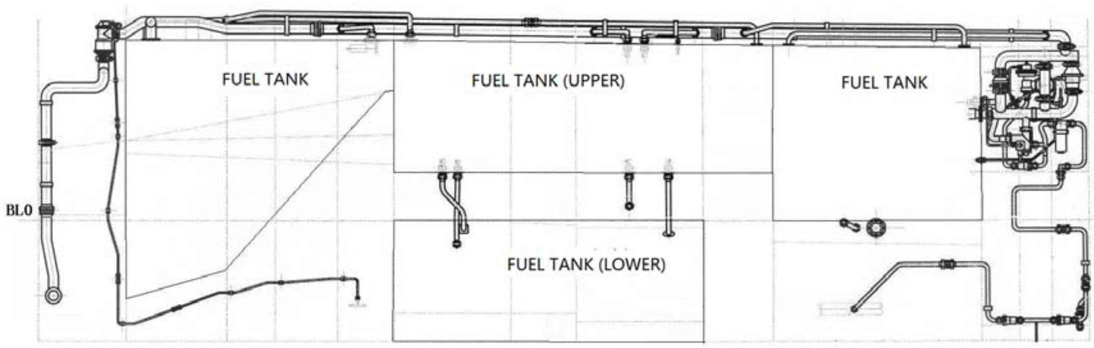


Figure 3-4 2-D System Drawing - Side View [44]

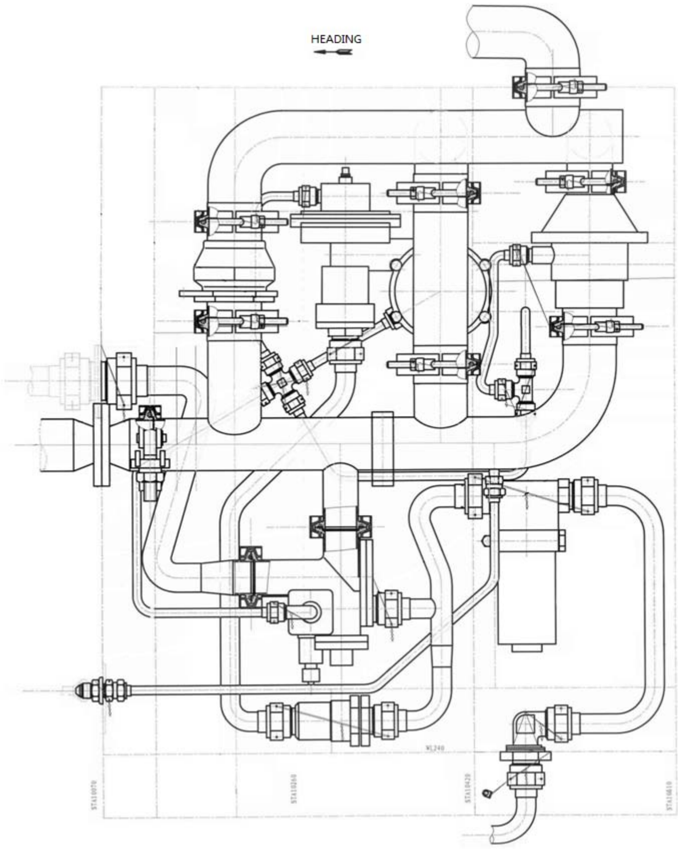


Figure 3-5 Detail View from the Side View [44]

Step 1: According to the supposed assembly process nodes definition in the above table, system installations are in the level 4.

Step 2: Then, the process planner would divide the drawing into many subassemblies based on his understanding of the drawing.

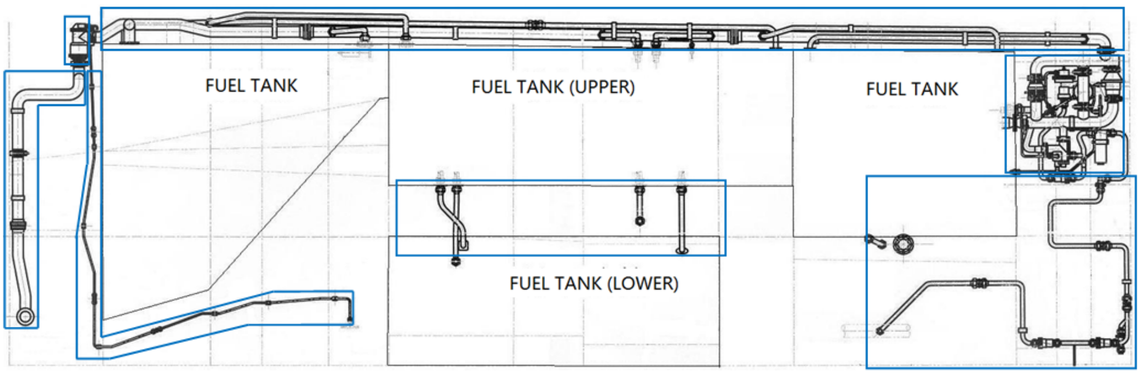


Figure 3-6 Subassemblies of the Drawing

In this example, the drawing is subdivided into some subassemblies (blue boxes in the figure).

- Installation of the finished products (each finished product for one subassembly)
- Installation of the upper fuel tank connection pipes
- Installation of the pressure control pipes
- Installation of the venting pipes
- Installation of the pressure release pipes
- Installation of the pressure connection pipes
- Installation of the fuel system air bleed pipes

Possible tooling, equipment requirement and assembly accessibility verification are considered in this step.

Step 3: Produce the text-based assembly process plan documents. A sample of text based assembly plan refers to Appendix B.

3.2.4 Problem Analysis

It seems that there is enough information provided for assembly process planning. The subassemblies are reasonable and clear. But an obvious problem should be seen is that both the side view and detail view have a poor representation of the installation positions for each part. Process engineers only have a general view of the bay structure such as station, buttock line, and water line coordinates. It is not a good solution to find the structure details in other structure drawings to help the process engineers understand the installation environment better, since it is very low efficiency and time consuming.

Dozens of problems are found when it comes to the practical installation. The figures below show the practical installation of the example.

Figure 3-7 The Installation of Detail View (Upper) [44]

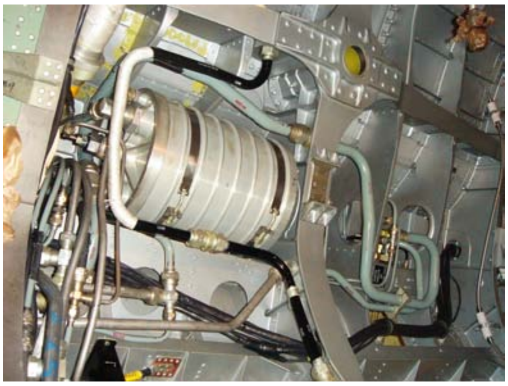


Figure 3-8 The Installation of Detail View (Lower) [44]

More potential problems are found in the practical assembly. Some problems are listed below.

- Collision is detected between the black cable harnesses and yellow fuel pipes behind the structure frame. Since these vent fuel pipes are in high temperature, to prevent the high temperature damage from cable harnesses, white asbestos protectors are fit on the pipes (Figure 3-7).
- Low clearance is detected between the black fuel system pipe and hydraulic reservoir. To protect the fuel pipe, white asbestos protectors is fit on it (Figure 3-8).

- Low clearance and some collision are detected among fuel pipes, hydraulic pipes and cable harnesses behind the frame.(the lower figure)

For traditional method used in this example, the assembly process planning is working on the assumption that there are no other systems' parts nearby in the installation area which is impossible in most cases. A prefect assembly process planning would become scarcely free of errors and even inoperable when different assembly plans of other systems come together.

Hence, the main problems of current process method can be concluded as below:

- The initial assembly process planning is mainly based on process planners' personal experience and imagination which lead to immense assembly problems in real work.
- The members in the process planning group design one's own parts isolated. They do not know the whole layout of the aircraft systems. For instance, planners of ECS do not know about the installation of electrical power system.
- It is often too late to find the practical assembly issues which need spending more time and high cost to change the process and product design. What is more, when changes are found to be continuous, it is hard to configuration control and quality control.
- It is difficult to build a full scale physical prototype to guide the assembly process planning because of the high cost and time-consuming work.

3.3 Research Methodology

3.3.1 The Methodology Framework

The aim of the research is development of a process design method to represent aircraft system assembly process in 3-D way. In the previous literature, many researches concentrate on evaluation of digital manufacturing in terms of operator learning [33], management learning [34] and simulation benefits [31]. Few references mentioned structure assembly process design in 3-D environment while little research is found for aircraft system assembly. Thus, the hypothesis is to propose an integrated process design method in a pure 3-D environment which covers from conceptual design to manufacturing stage.

The figure below shows the research methodology framework based on Fan's integrated CAD method [28] and Simpson's abstract DFA principles [27] in a concurrent engineering process.

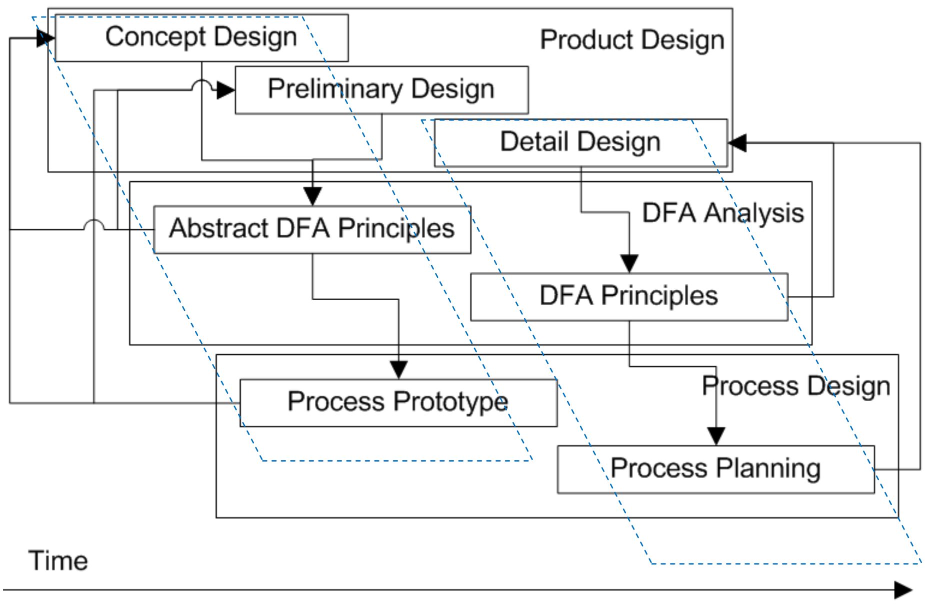


Figure 3-9 Research Methodology Framework

The ideal situation is applying a universal research methodology. However, it is impractical since there are three research activities relevant to different aspects of process design. It is difficult to take these research activities following a single specific methodology. Besides, practical difficulty is found that it will be out of the research scope. The production, QC and maintenance requirements of digital process plans would make it more complicated. Furthermore, since the concerns of product design in different stages are quite different, it is necessary to bring process design into correspondence with product design for different stages. Therefore, the methodology will be developed respective in the methodology framework.

3.3.2 Methodology in Early Design Phase

Although some previous researches [7] suggest that process design should be considered as early as possible in concurrent engineering model, process design itself cannot take place without any design data input. Therefore, to formulate a possible research methodology for early design phase, it is necessary to look at how DFA is applied for assembly design in early design phase first. Then following assembly process options can be proposed based on initial assembly design.

The application of DFA for manual assembly is discussed In Boothroyd and Dewhurst's book. General design guidelines are given in terms of two areas, for part handling and for insertion and fastening. They book authors recognise that there are two main factors relevant to assembly cost:

- The number of parts in a product
- The ease of assembly of the parts [7]

They also propose a method to measure DFA index (assembly efficiency) of a proposed design.

$$E_{ma} = \frac{N_{\min} t_a}{t_{ma}} \qquad \textbf{(3-1)}$$

Where,

E_{ma} is the DFA index or known as assembly efficiency.

N_{min} is the theoretical minimum number of parts.

t_a is the basic assembly time for one part. According to the Boothroyd and Dewhurst's book, the ideal basic assembly time is the average time for a part that presents no handling, insertion, or fastening difficulties. The experience database based volume is about 3s.

t_{ma} is the estimated time to complete the assembly of the product [7].

However, N_{min} is estimated in an ideal situation where separate parts are combined into a single part unless, as each part is added to the assembly, some specific criteria given by the book authors should be met. Hence, it is difficult and subject for calculation in concept design. What is more, the original DFA method is more suitable for small pieces of parts instead of large ones in aircraft industry. The book authors admit when using the original DFA method for large assemblies, the method is limited in estimating accuracy. To solve the problems, they propose an approach which is base on large assembly database [7].

For the aircraft system design in concept phase, both the general DFA design guidelines and estimation method of original DFA method are not practical to guide the early design.

In the literature review, Simpson [27] proposes the abstract DFA principles combined with selection Decision Support Problems (DSPs) to help solving the issue of application DFA in concept design.

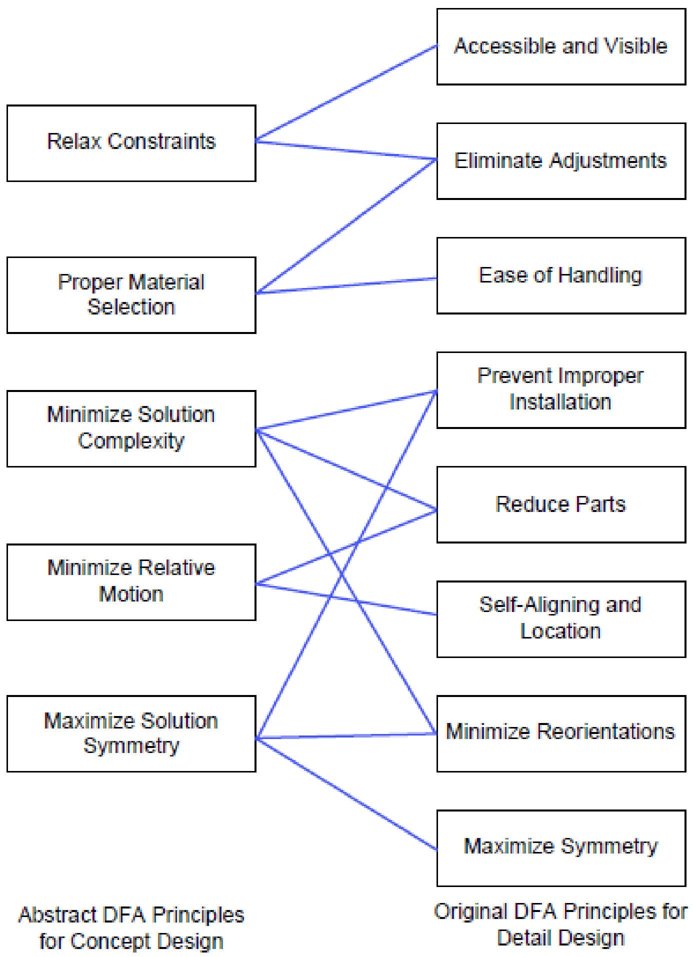


Figure 3-10 Relationship between Abstract DFA and Original DFA [27]

The figure above illustrates the abstract DFA principles on the left side. In Simpson's approach, abstract DFA method is used as selection criteria of initial solution concepts. Since this research focuses on the process design in a digital manufacturing environment, it is not necessary to discuss too much detail in actual concepts design. Abstract DFA in this research is considered as a design method to simply propose assembly design based on GDP.

The research methodology for early design phase is described as below.

Step 1: Input defined conceptual 3-D geometry of aircraft layout from GDP.

Step 2: Propose possible initial aircraft system assembly geometry based on system function definition and abstract DFA principle.

Step 3: Propose process definition based on possible assembly strategies.

Step 4: Select the assembly process strategy.

Step 5: According to the selection of assembly process strategy, improve 3-D geometry for next design phase usage.

This methodology is shown as below.

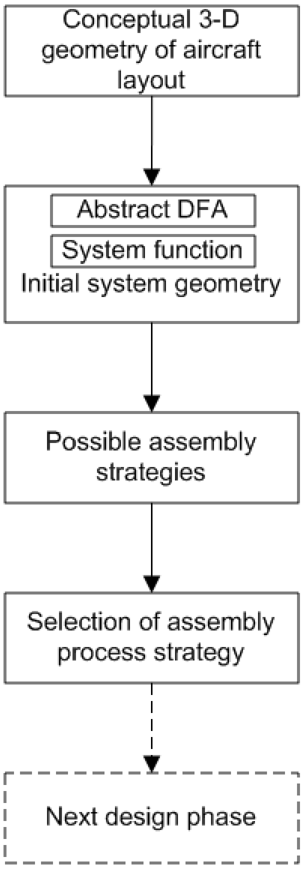


Figure 3-11 Methodology for Early Design Phase

3.3.3 Methodology in Detailed Design Phase

Because of the reasons described before, the specific methodology was chosen for detail design phase as below:

Step 1: Define detailed 3-D geometry of aircraft system assembly.

Step 2: Propose possible process options including initial work breakdown structure in general.

Step 3: Simulate the assembly in 3-D environment. Detect both product design and process design problems.

Step 4: Improve the product design and process design if necessary.

Step 5: Compare the solutions.

Step 6: Produce detailed work breakdown structure.

Step 7: Produce detailed 3-D assembly plans based on previous simulation results. Incorporate process specification and QC requirements.

This methodology is illustrated in the figure below.

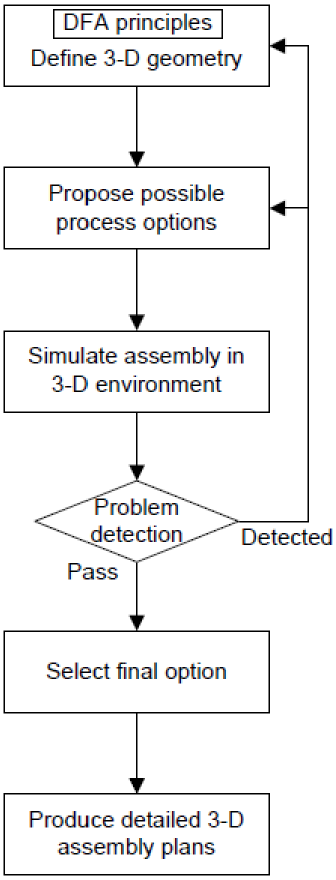


Figure 3-12 Specific Research Methodology for Detail Design Phase

3.3.4 Software Chosen for Detailed Design Phase

3.3.4.1 Ideal Process Design Software

CATIA is introduced in the literature review that it is a 3-D CAD/CAM/CAE software widely used in aircraft industry. Although CATIA has some CAM modules, most of these modules are about machining. For process design usage, another software developed by Dassault Systems namely DELMIA (Digital Enterprise Lean Manufacturing Interactive Application) is a digital manufacturing solutions which allows manufacture engineers to virtually define, plan, create, monitor and control all production processes from early process planning and assembly simulation to a complete definition of the production facility and equipment [35].

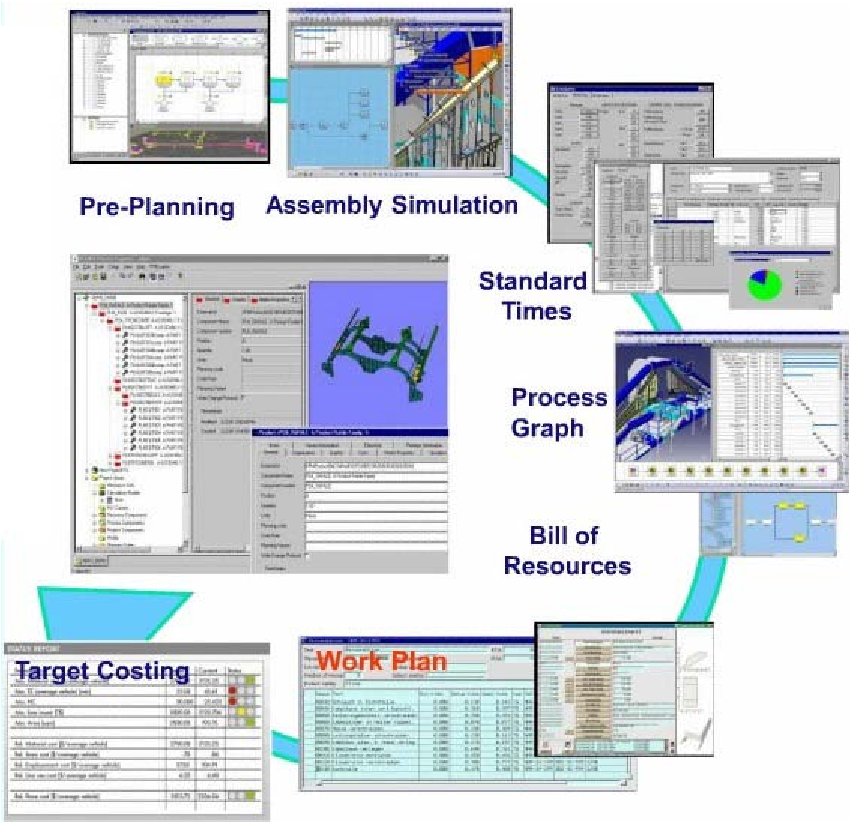


Figure 3-13 DELMIA Solution [35]

The one of the DELMIA tool, namely DPM Envision Assembly is an ideal module for this research task. Envision Assembly tool facilitates development of multilevel assemblies, sequences, part paths and process documentation. Design and manufacturing engineers analyze various scenarios to determine the best assembly process and disassembly/reassembly of the product. Then, the simulations are recorded and used for shop floor instructions, maintenance instructions and training [36].

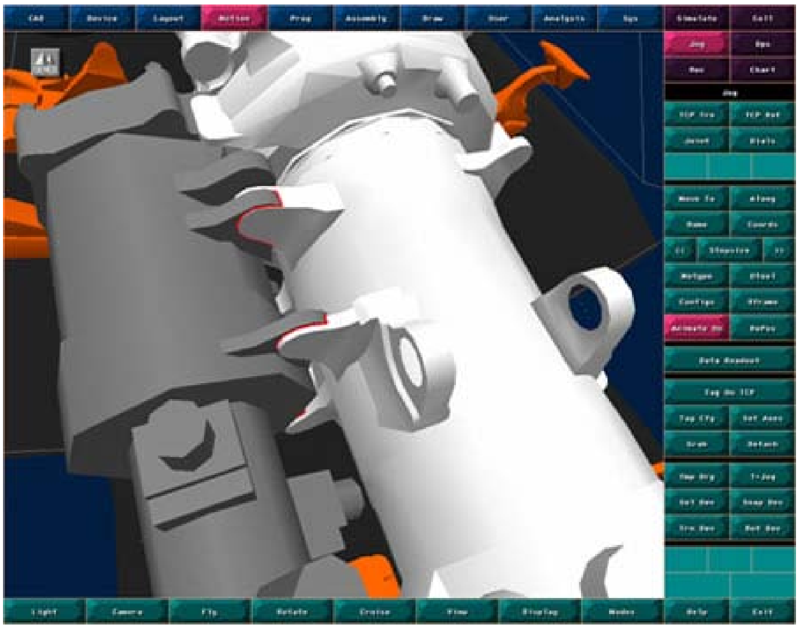


Figure 3-14 Envision Environment [37]

However, due to the difficulty to access license of DELMIA in the University, the research has to choose and evaluate other possible software to meet project requirement.

3.3.4.2 Evaluation of Alternative Software

As mentioned in the literature review, 3DVIA Composer is a XML lightweight CAD based 3-D representation software developed by Dassault Systems. The typical application fields are:

- Technical illustrations
- 3-D animated assembly instructions
- Manufacturing shop floor instructions
- Maintenance instructions
- Light weight project reviews deliverables
- Training Materials
- Sales and Marketing presentation

It can be seen that some function of 3DVIA and DELMIA Envision are very similar in some extent. A further comparison is made based on the research requirements in the table below.

Table 3-2 Comparison between DELMIA and 3DVIA

	DELMIA Envision	3DVIA Composer
Assembly Sequence Representation	Nodes in tree structure	Key markers in time line
Assembly Path Planning	Manual mode, time consuming automatic calculation mode	Manual mode, time consuming automatic calculation mode
Collision Detection Mode	Manual and automatic detection in real time	Manual and interactive collision detection after path planning
Clearances Detection Mode	Manual and dynamic automatic	Manual and automatic clearance checking after path planning
Cable Harnesses Assembly Simulation	Change shape in real time to reflect the geometric constraints	Not include
VR Environment and Collaboration	Flexible and powerful function	Weak and limited VR and collaboration function
System Integration	Seamless integrated with CATIA data and PDM system	Need import CATIA data to lightweight data with user controlled options. Data can be integrated in PDM system and other applications or website pages supporting ActiveX.
3-D Assembly Instruction	With 3-D notation when playing CATIA data in real time. Recorded video files (avi format) for shop floor usage.	Interactive 3-D instruction in real time playing mode. Recorded video files (avi format) for shop floor usage.

This comparison can be concluded that 3DVIA Composer has most of the function needed for the research which DELMIA Envision has, except the cable harnesses assembly simulation. An obvious advantage of 3DVIA is its interactive instructions will bring the operators in the shop floor a better 3-D experience. In addition, the XML technology based 3-D documents are more suitable for collaboration and communication in website based PDM system which benefit from small file size. Thus, the practical methodology used in detail design phase is illustrated in the figure as below.

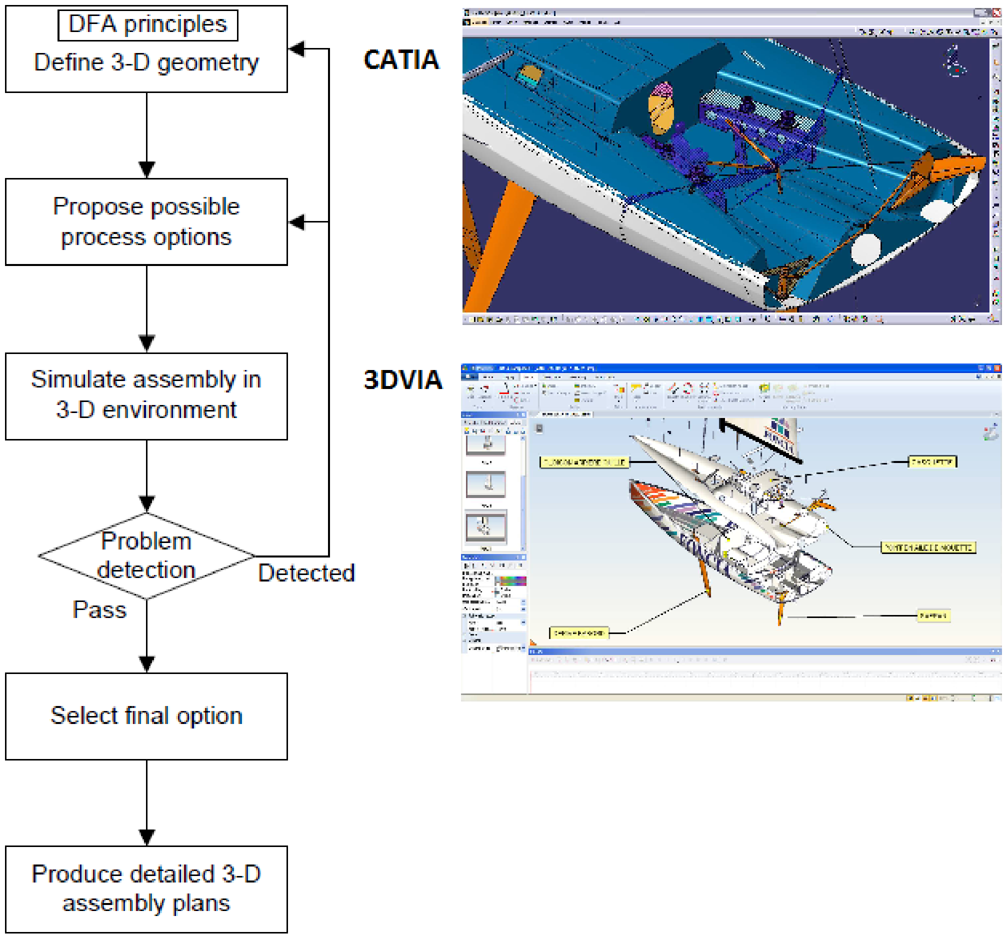


Figure 3-15 Practical Research Methodology for Detailed Design Phase

3.3.4.3 Validation of the Chosen Software

It is known that system assembly process planning in final assembly plant is very challenge due to the complexity of systems layout and the difficulty of obtaining related information. According to the comparison in literature review, lightweight CAD data has its special advantage on 3-D representation. Although investigation shows 3DVA's XML based smg format support importing original CATIA solid model graphic data, it is still necessary to verify the needed function of the software in assembly simulation.

The validation test will use a detailed car system CAD data of CATIA as an initial test due to availability of data [41]. The assembly model will be disassembled from the installed position. After that, the assembly result will be reversed in time line to represent the assembly process.

The general test flow is described as below:

- Import raw CATIA product models to 3DVA Composer.
- Analyze the tree structure of CAD data, decide the assembly strategy.
- Assembly simulation in 3DVIA Composer.
- Function test.

The figure below shows the detailed CAD data both in CATIA and 3DVIA systems.

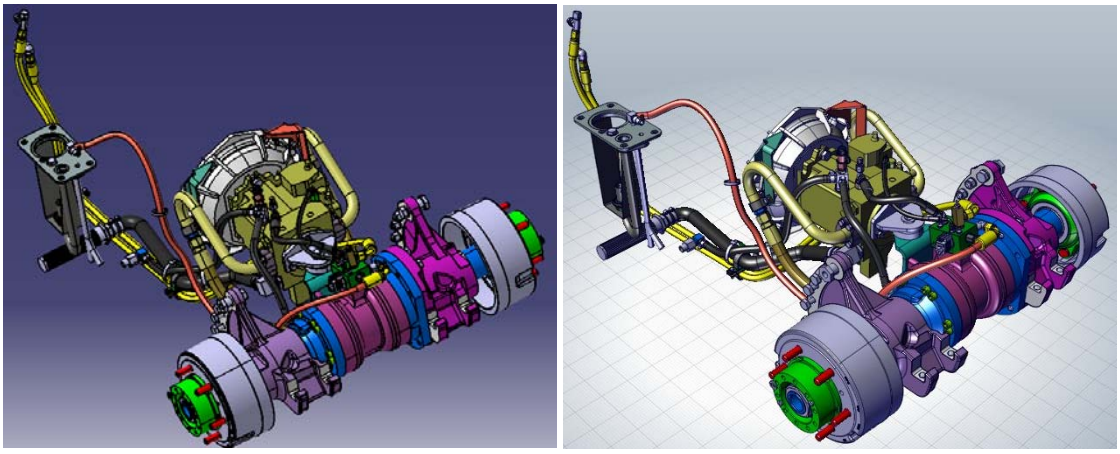


Figure 3-16 Models in Different CAD Systems

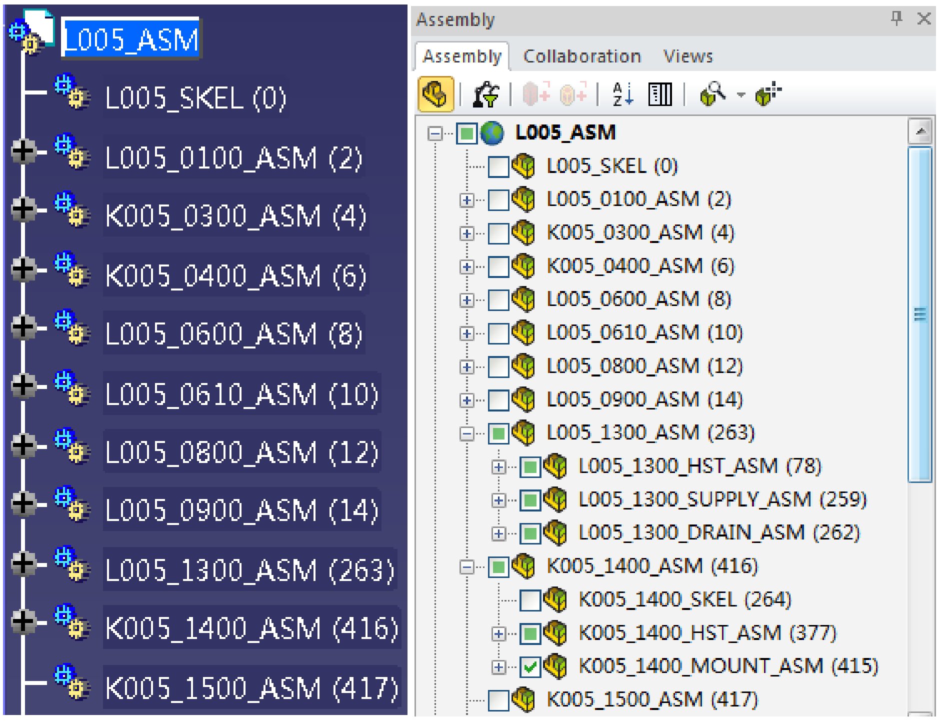


Figure 3-17 Specification Tree Structures in Different CAD Systems

The CAD model contains two subassembly parts which are L005_1300_ASM (263) and K005_1400_ASM (416). Pipes installed between the two main parts will be simulated to find out potential assembly problems.

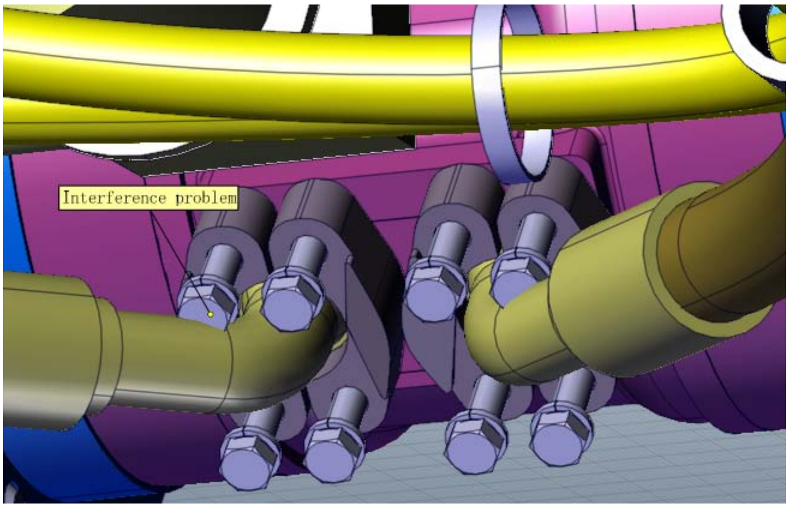


Figure 3-18 Problem Detected in 3DVIA Assembly Simulation

The figure above illustrates the interference problem detection when simulating the bolts assembly into designed installation position. As a basic function needed in assembly planning and shop floor application, measurement has also been tested in both CATIA and 3DVIA.

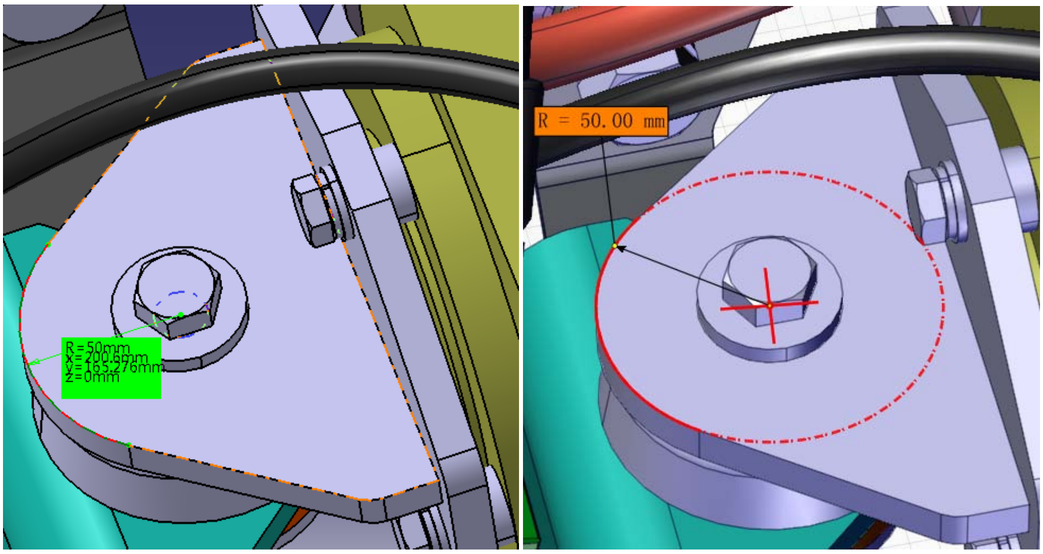


Figure 3-19 Measurement in Different CAD Systems

It can be seen from the figure above, the measurement result in 3DVIA (right side) environment is in accordance with CATIA (left side).

General conclusion can be made through the simple test that 3DVIA Composer can satisfy the demand for further assembly simulation of case study. However, what should be pointed out is the function test is in an ideal environment because the surrounding car structures are not included. In most simulation situation, structures are the main constraint of assembly activities. The future assembly simulation of case studies will base on detailed CAD data including both structures and system parts.

3.3.5 Methodology for Development of 3-D Process Planning Application System

In the present 2-D drawing and text-based process planning model, the results of process design are described in paper documents. Obviously, a new application system is needed for the process planning results representation and management in shop floor, since the old paper based model cannot adapt the digital process requirement.

Thus, the research methodology can be formulated as below:

Step 1: Investigate the requirement.

Step 2: Develop the framework of integrated process planning information system.

Step 3: Develop 3-D assembly process planning representation in shop floor.

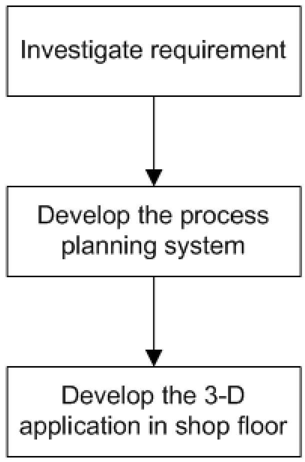


Figure 3-20 Research Methodology for Process Planning Application System

3DVIA system uses XML based lightweight CAD data as the main document storage method, which has an advantage of integration in website. 3-D Assembly plans can be integrated in website based PDM system. Since 3DVIA system support second development according to ActiveX Application Program Interface (API), a customized application system can be developed.

3.4 Summary of Chapter

This chapter has stated the research methodology by which the current situation was investigated before. The research methodology framework is introduced first which covers the main product development process. Specific research methodologies are formulated respectively under the framework.

The next chapter will apply research methodology into early and detail design cases. The development of assembly process planning system will be covered in chapter 5.

4 Research Case Study

4.1 Introduction

Since the research methodology developed in chapter 3 covers different design phases of product development process, three relevant cases are chosen to apply the methodology respectively.

The FW-11 project which is in the conceptual design in 2011 is considered as the case study of early design. As introduced before in chapter 1, most of the AVIC students begin their IRP work based on GDP design results. One of the author's classmates Mr. Xiangyang Wang, whose IRP topic is aircraft fuel system prognostics and health management will start the research based on fuel tanks definition from GDP. Schematic diagrams of FW-11 fuel system will also be developed in his research which creates an opportunity to propose the system geometry and look into the aircraft system process design in early product design phase. Hence, FW-11 fuel system is chosen as the early design case study.

The process design in detailed design phase, which is particularly complex will use two typical cases for the research. Flying Crane fuel system and Vehicle Design (AVD) A-8 ECS are considered as the cases of detailed design. Detailed design case study 1 will use CATIA CAD data of Flying Crane wing fuel system from detail design. While detailed design case study 2 is a more complicated case which based on the detailed CAD data of A-8 ECS. Attention should be paid to these detailed CAD data that these CATIA solid models do not contain sufficient assembly information such as parts connection and fastening although these data come from detail design phase. Therefore, detailed assembly information is needed to be defined in CATIA first.

4.2 Early Design Case Study

4.2.1 Initial System Geometry

The FW-11 conceptual design has finished the general definition of fuel tanks which are located in three positions – left wing, right wing and the bottom of cabin. The figure below shows the configuration of FW-11.

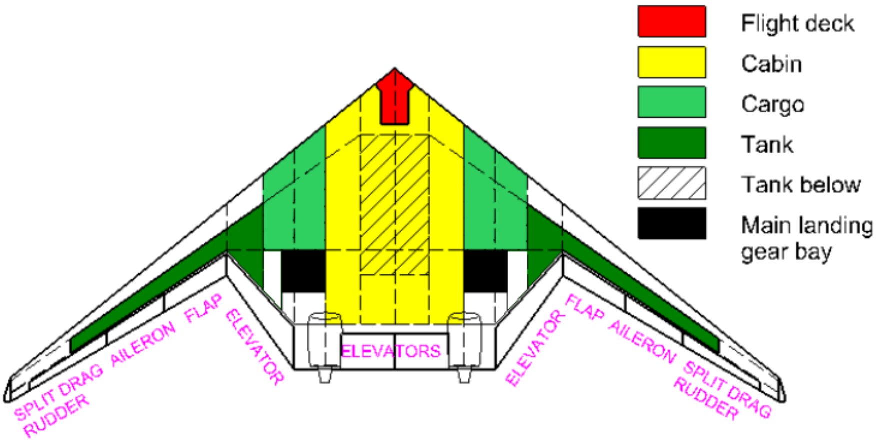


Figure 4-1 Configuration of FW-11 [45]

Then, the general location of fuel tanks is drawn by the author in 3-D environment based on the GDP report which is the configuration and geometry of FW-11 conceptual design [45].

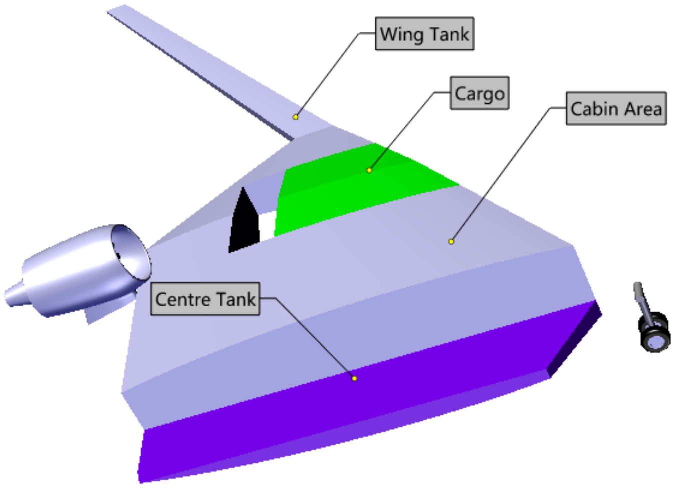


Figure 4-2 General Location of Fuel Tanks

A more detailed definition of fuel tanks and schematic diagrams of FW-11 fuel sub-systems are given by Mr. Xiangyang Wang's research.

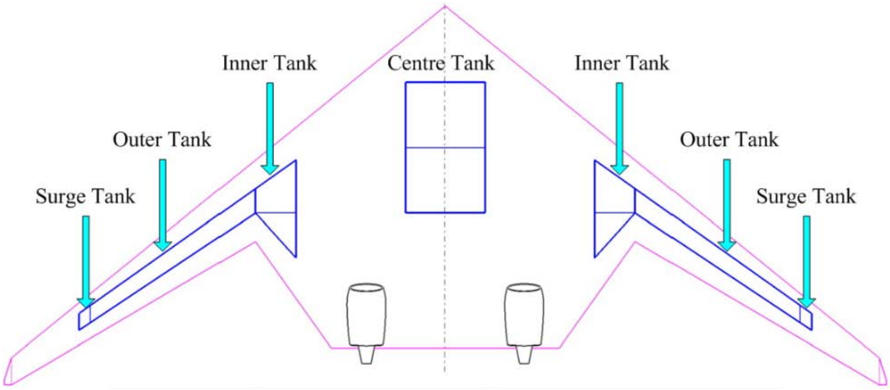


Figure 4-3 Fuel Tanks Arrangement of FW-11 [46]

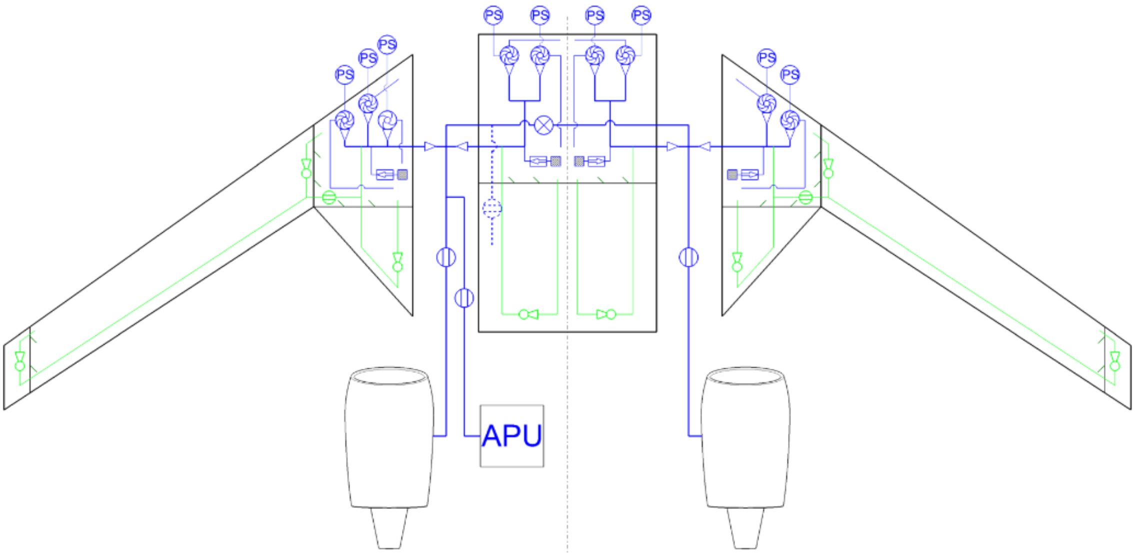


Figure 4-4 Fuel Feed Sub-system of FW-11 [46]

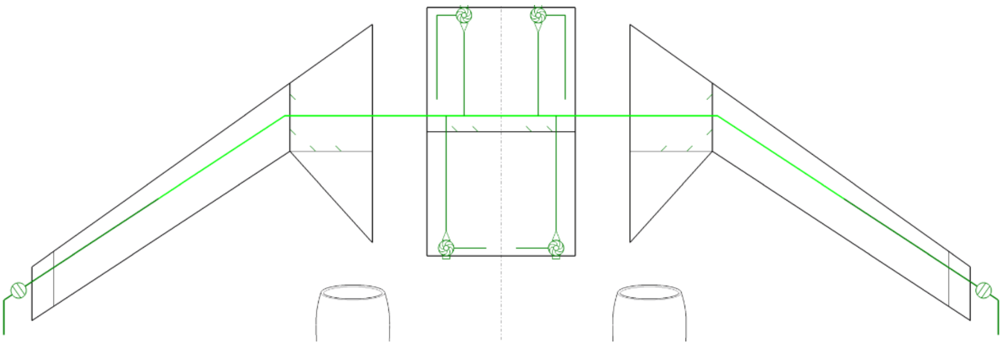


Figure 4-5 Jettison Sub-system of FW-11 [46]

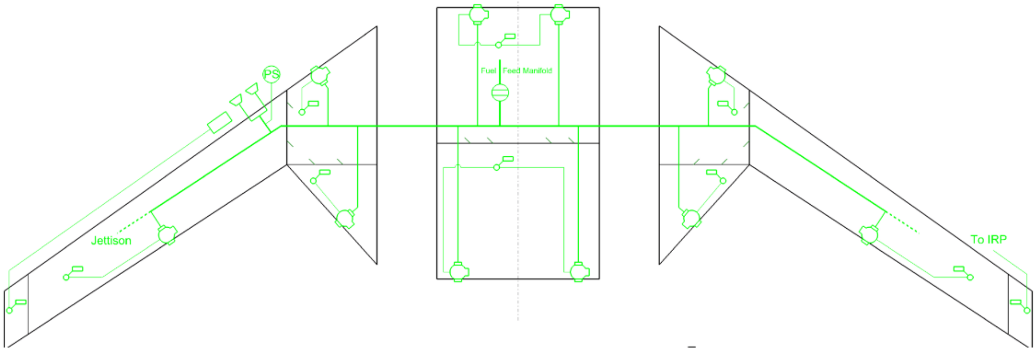


Figure 4-6 Refuel Sub-system of FW-11 [46]

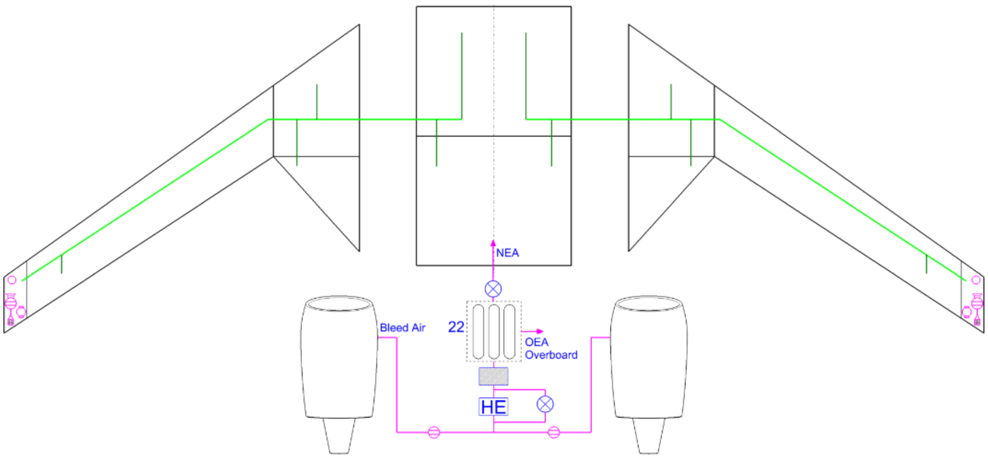


Figure 4-7 Vent Sub-system of FW-11 [46]

The five figures above are the only fuel system data can be obtained for this case study. However, schematic diagrams do not present sufficient information about installation of system parts, since system components in the schematic diagrams do not reflect whether there are other assembly constraints like structure which would lead to change the system assembly design.

In the FW-11 GDP report, the pressurized volume is defined in blue lines.

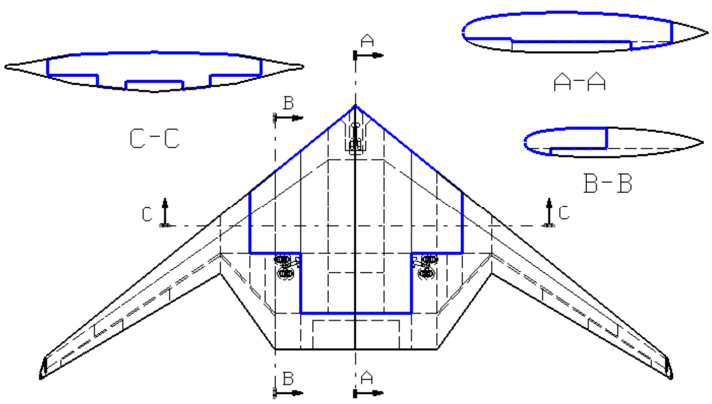


Figure 4-8 Definition of Pressurized Volume [45]

According to the definition, it is not recommended for fuel system pipes to break the defined pressurized volume when designing the system layout of pipes.

As the methodology developed in chapter 3, abstract DFA principle is used to help simplifying the assembly design in conceptual design phase. The table below shows the application of abstract DFA principle in this case study.

Table 4-1 Abstract DFA Principle in FW-11 System Design

Abstract DFA Principle	Assembly Design Guidance	Application into System Geometry Modelling
Relax Constraints	Consider accessibility	Arrange the pipes layout for ease assembly.
Proper Material Selection	Use common material & standard sizes	Not available for the modelling at this phase
Minimize Solution Complexity	Simplify and standardize pipes	The diameter of all pipes is set as 50.8mm (2in) since fuel flow is not known at this stage.
Minimize Relative Motion	Design the system for easy alignment. Reduce system parts if possible	Pipes are arranged in parallel when different pipes of sub-systems have the same direction of layout. Finished product (such as pumps, valves, sensors) and connectors are considered as part of the pipes. No supports, brackets and fasteners are modelled.
Maximize Solution Symmetry	Design the pipes layout for symmetry	Pipes close for easy sharing of brackets if possible.

Following by this guidance, general system geometry can be designed in 3-D environment. The figures below illustrate the initial system assembly geometry modelling in CATIA by the author. The pipes with yellow colour are fuel system models.

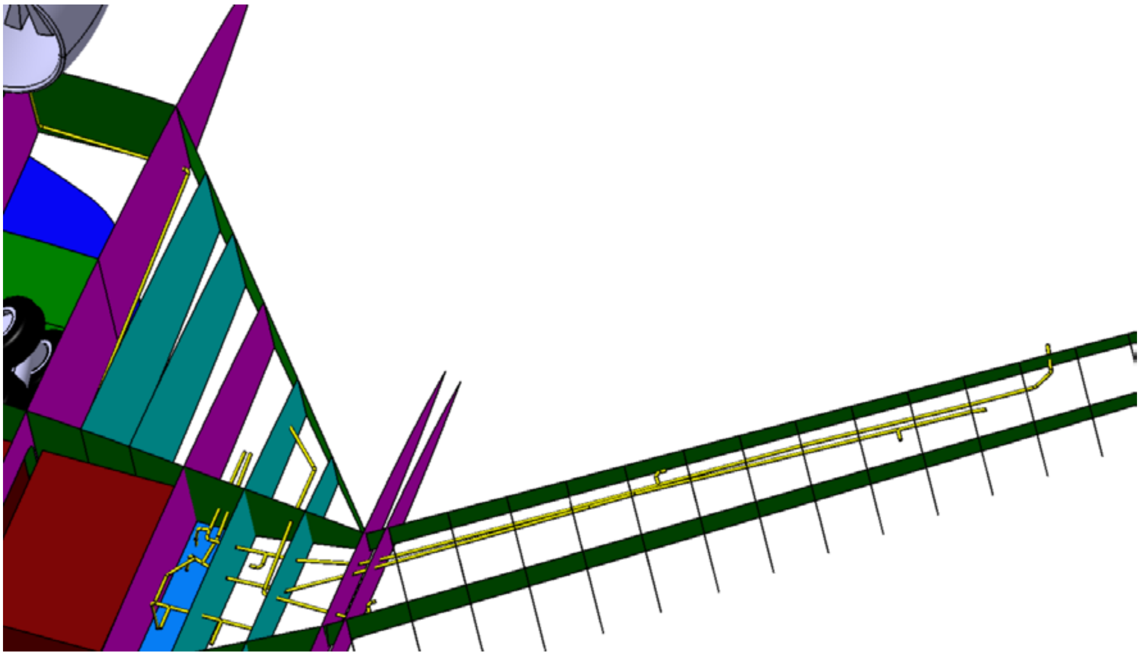


Figure 4-9 Initial System Assembly Geometry of FW-11

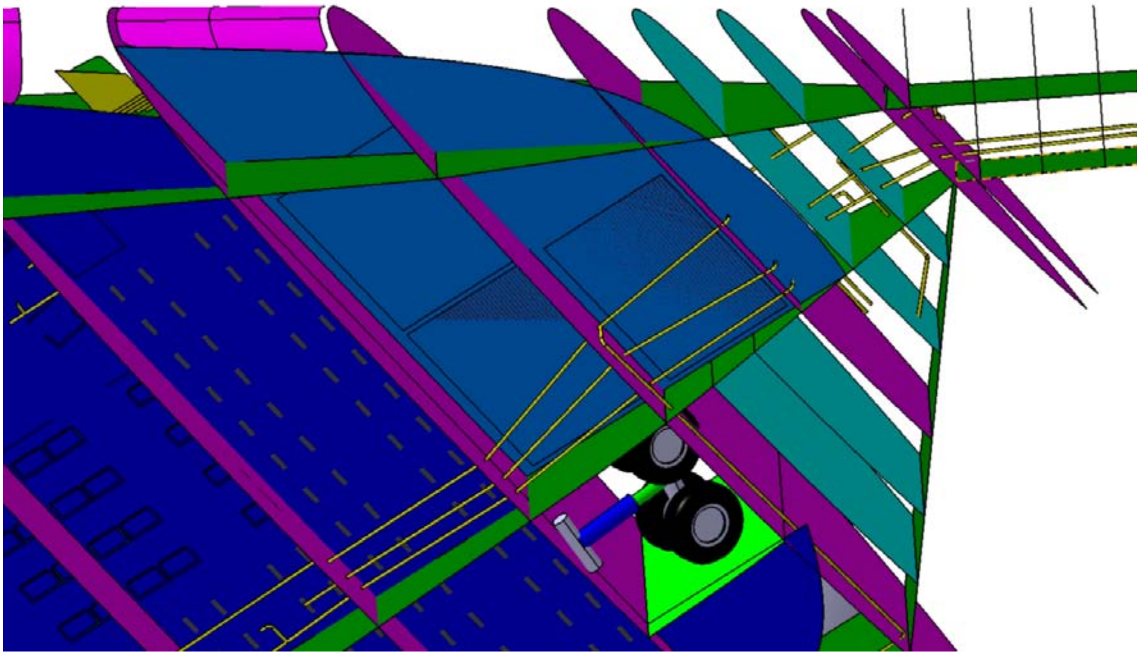


Figure 4-10 Initial System Assembly Geometry of FW-11 (Bottom View)

4.2.2 Possible Process Options

Early assembly process design mainly concerns how to develop manufacturing strategies. For the FW-11 system assembly case, one of these concerns is to decide the general work breakdown structure of fuel system. However, this is found to be difficult to formulate. It is known that conventional aircraft can be simply divided into some main parts such as wings, fuselage and tail. In the case of rear engine configuration of conventional aircraft, process definition of fuel system can be generally divided into wing fuel system and fuselage fuel system. But flying wing aircraft cannot easily follow this traditional process definition to divide it into some parts for manufacturing, since there is no fuselage anymore. So is the case with the process definition of FW-11 fuel system.

In FW-11 GDP report [45], the aircraft is divided into inner wing and two outer wings by geometry design team. The figure below demonstrates the product geometry definition of FW-11.

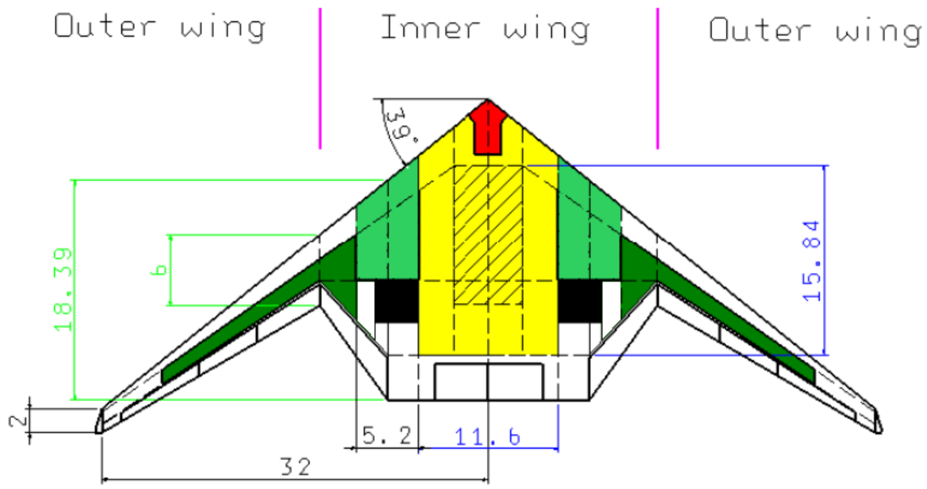


Figure 4-11 Product Definition of Inner Wing and Outer Wing [45]

This figure above shows the product designer's view of the aircraft. Since product designers are not always familiar with the process requirement and manufacturing capacity, in some cases however, process definition is different from the product definition. Hence, two process definitions can be proposed by process engineer for the FW-11 fuel system assembly.

- Option 1: The process definition is the same as product definition which is shown as below.

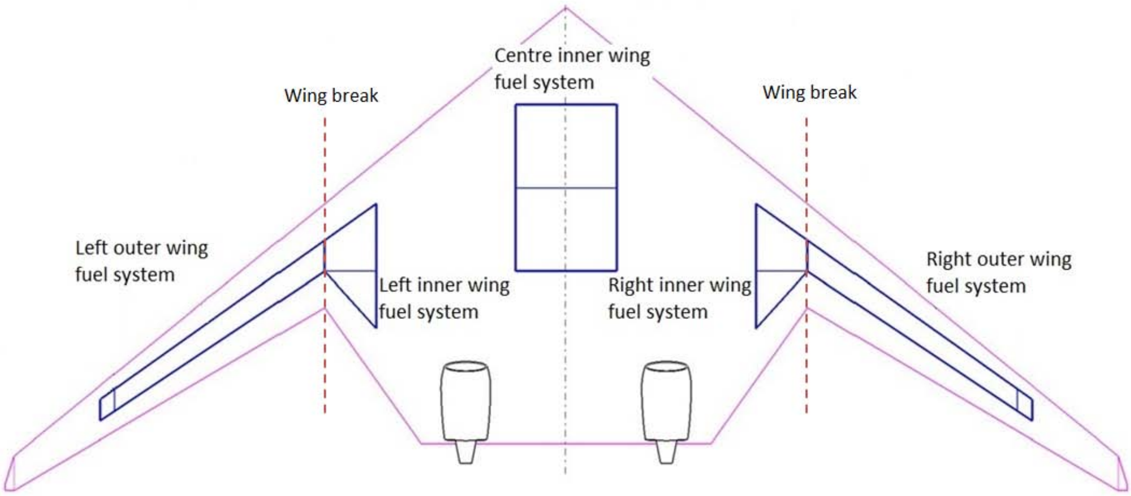


Figure 4-12 Process Definition of Fuel System for Option 1

- Option 2: According to the FW-11 general configuration, the two fuel tanks (product definition as inner tank and outer tank in figure 4-3) are arranged closely, it can be considered the two tanks as outer wing fuel system in process definition of option 2.

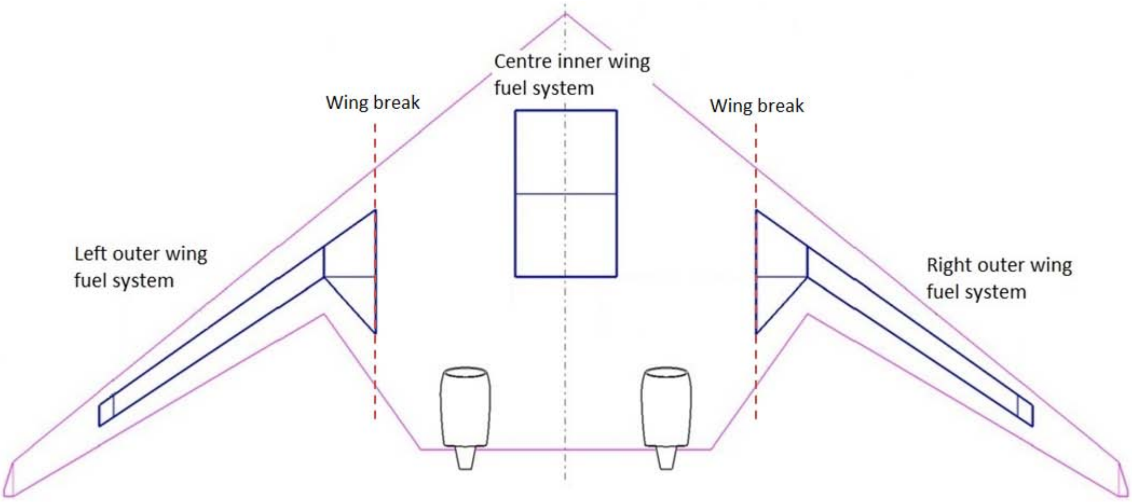


Figure 4-13 Process Definition of Fuel System for Option 2

4.2.3 Selection of Process Strategies

Actually, the essence of selection of the two process options is how to choose the wing break or wing jointing interface with a system assembly view. The two options of different wing jointing interface from the initial fuel system geometry are shown respectively.

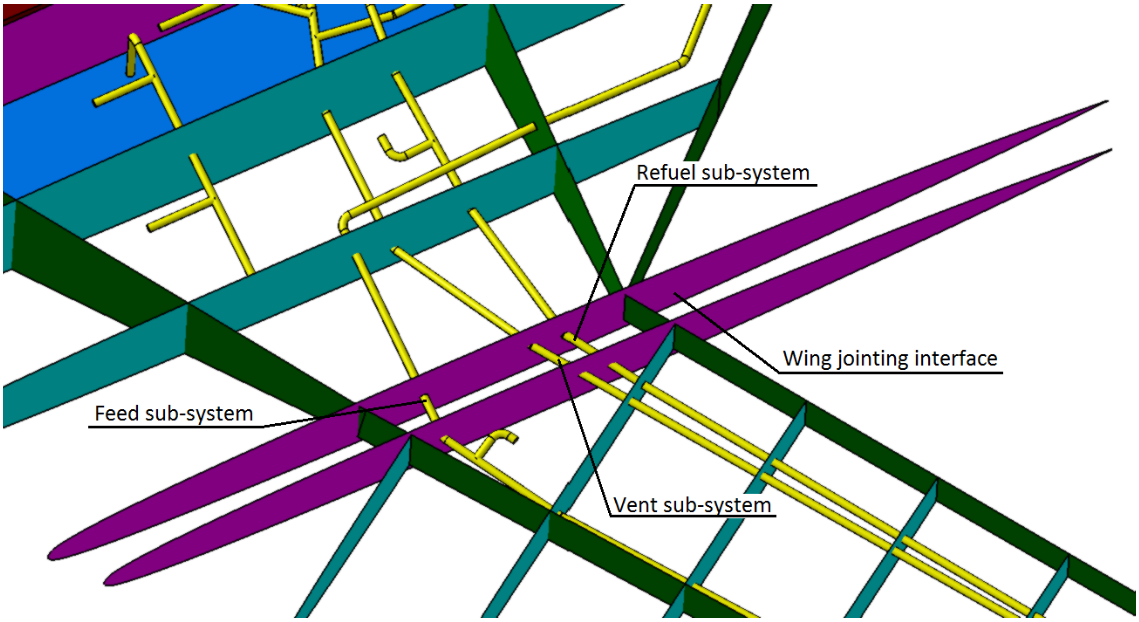


Figure 4-14 Fuel System at Wing Jointing Interface of Option 1

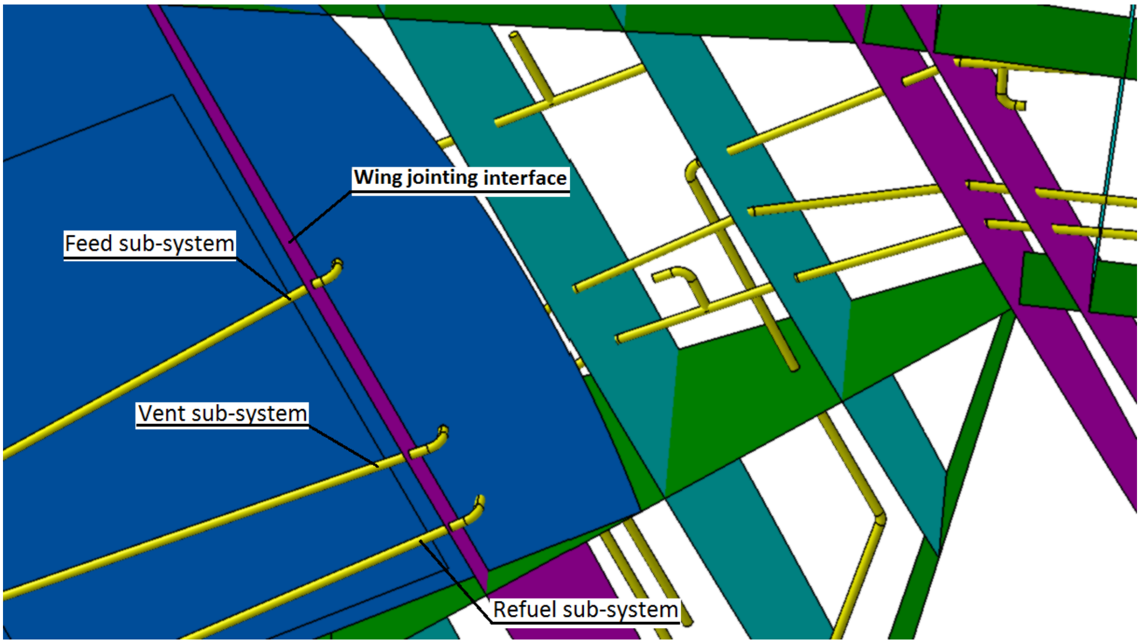


Figure 4-15 Fuel System at Wing Jointing Interface of Option 2

In option 1, the wing jointing interface is designed between two fuel tanks which would lead to the reduction of fuel tank capacity. Because in work of wing jointing, fuel system pipes and wing jointing connectors are connected between the two fuel tanks, enough room should be left to meet the accessibility requirement. As a result of that, wing structure should also be changed. While in option 2, this situation does not happen since the other side of wing jointing interface is not in the fuel tank area. System and wing jointing connectors have a rich space for arrangement. Thus, with this system assembly view, option 2 is more reasonable.

This research tries to use an integrated view to help product design in early design phase. More factors of assembly process definition selection will be given in the table below.

Table 4-2 Comparison of the Two Options of Wing Jointing Interface

Factor	Option 1	Option 2
Geometry design	The wing break is designed at the place with minimum length of geometry.	The wing break is designed at the inner wing near the minimum length of geometry.
Fuel system design	Limitation of arrangement of system connectors. The capacity of two fuel tanks needs to be reduced to leave enough room for arrangement of system and wing jointing connectors.	More flexibility for arrangement of system connectors and pipes. The capacity of two fuel tanks may not be reduced since the other side of wing jointing interface is not in the fuel tank area.
Wing jointing	Structure should be changed since wing jointing connectors cannot be arranged in fuel tanks area. Enough space should be left for wing jointing structural parts and accessibility operation.	Enough space should be left for wing jointing structural parts and accessibility operation.
System assembly	Relative poor accessibility and assemblability.	Good accessibility and assemblability.

For the factors given above, option 2 is better than option 1. Thus, the 3-D geometry of conceptual design can be improved for next design stage usage.

4.2.4 Initial Conclusion of Early Design Case Study

Initial conclusion can be drawn that in early design phase, manufacturing strategy and assembly process definition can be made based on the proposed 3-D geometry, while abstract DFA principle helps simplifying the system modelling process. In the concurrent engineering model, process design involves in the early product development process to help improving product design.

4.3 Detailed Design Case Study 1

This case study is based on wing fuel system of Flying Crane airliner which is a 130-seat conventional airliner designed by AVIC students from 2008 to 2010 [47]. Choosing fuel system as a study case mainly takes account of the installation characters of fuel system parts. Because most of fuel system parts are installed in a relative separate space - the fuel tank, which makes fuel system assembly the typical case of installation in relative open environment - low assembly constraint case.

4.3.1 Detailed Geometry Modelling

The original CATIA models of Flying Crane fuel system are designed by former CAD team of the third cohort AVIC students. The author obtained the models from Dr. Shijun Guo who is the academic director of AVIC training programme. As mentioned before, the original CAD data from Flying Crane detail design is not sufficient for further assembly process planning.

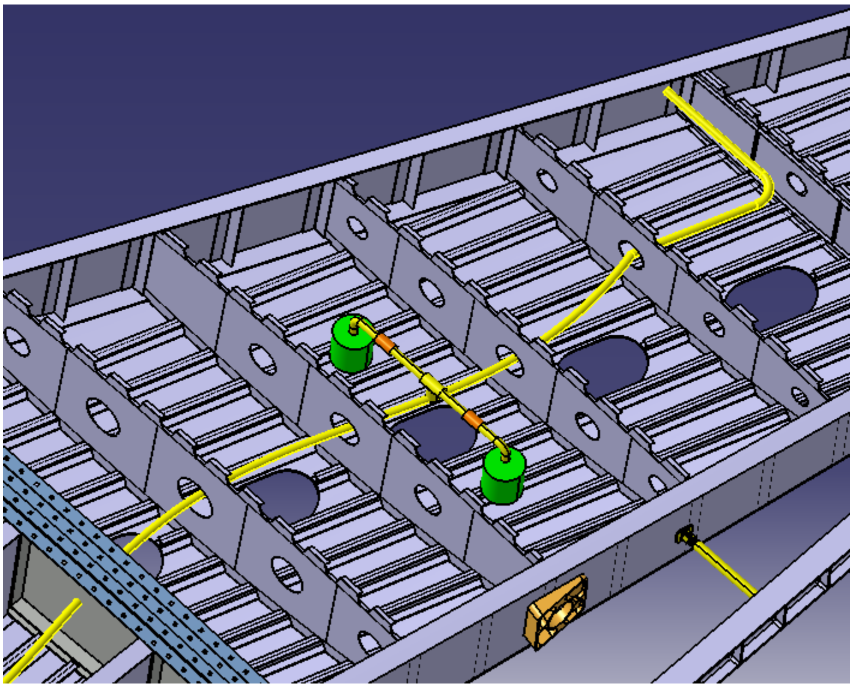


Figure 4-16 Original Fuel System Layout from Detail Design Phase (Right Wing)

According to the research methodology developed in chapter 3 (figure 3-12), the first stage is to define the 3-D geometry. However, it can be seen from the figure that the original fuel system design only have the general system layout information. Neither the pipes installation nor pipe sections information contains in this system solid model. Additional work has to be done base on the original models by using CATIA tubing and assembly design tools. The author has added the following details to the original fuel system model.

- Individual pipe definition including end style.
- Pipe connection.
- Supporting components.
- Fastening information.

Since the system assembly modelling contains high level of details, more research activities about system modelling including the application of DFA principles refer to Appendix C - Case Study 1 Detailed Modelling and Simulation.

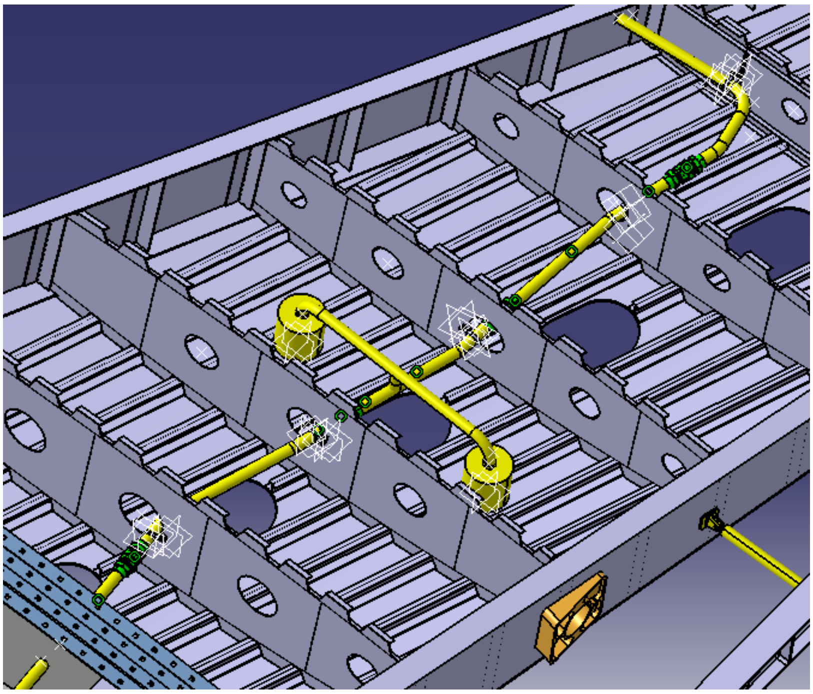


Figure 4-17 Detailed Fuel System Models with Assembly Information (Right Wing)

This figure illustrates the revised fuel system assembly design. Fuel pipes are redesigned to separate into sections with end styles. Pipe supports, brackets and fasteners are added in the models.

4.3.2 Propose Process Options

In the second stage, possible process options are proposed base on the assumption of certain process capacity, work breakdown structure or sub-contact task interface. To minimize the research scope, process options are limited in manufacturing of one company in this case study.

The Flying Crane fuel system components are mainly arranged in inner wing and central wing tanks. It is clear through the figure above, fuel system is divided by two main ribs into three areas: central wing, left inner wing and right inner wing fuel system. In addition, four fuel pumps are arranged in each inner wing tank.

Based on the product assembly analysis, there are two process options for wing fuel system assembly generally.

- Option 1: Joint the central wing and inner wings first, and then install fuel system parts into fuel tanks.
- Option 2: Install fuel system parts into central wing and inner wings tanks first, and then joint wings.

According to the supposed assembly process nodes definition of final assembly plant described in chapter 3, the preliminary process work breakdown structure of the two options can be defined as below.

In option 1, because fuel system parts are installed after wing jointing, these installations belong to level 3 – wing jointing related installations.

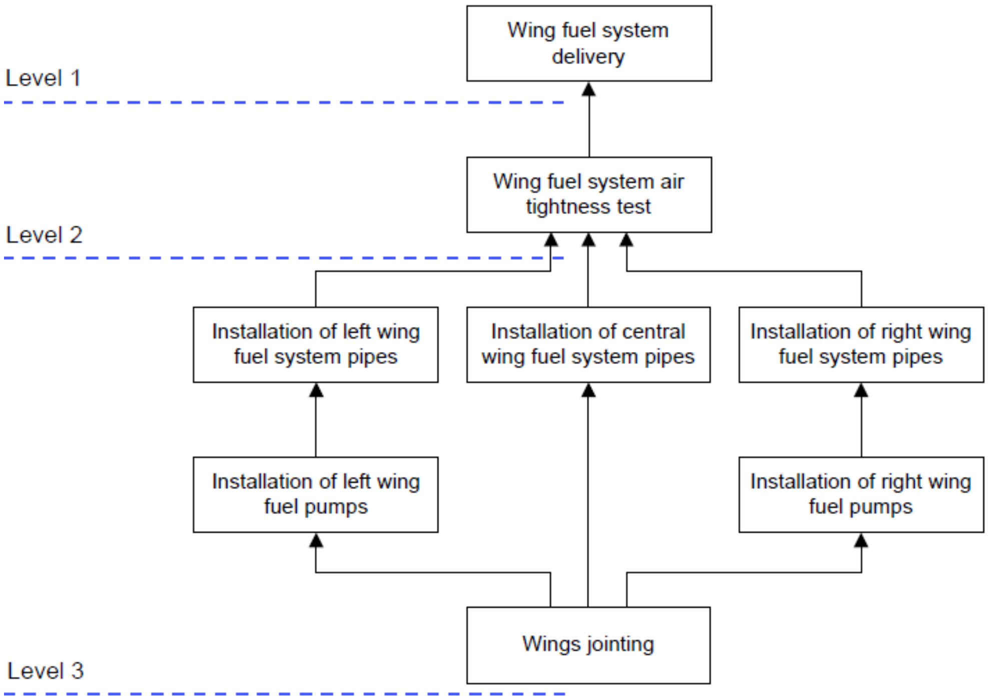


Figure 4-18 Proposed Work Breakdown Structure of Option 1

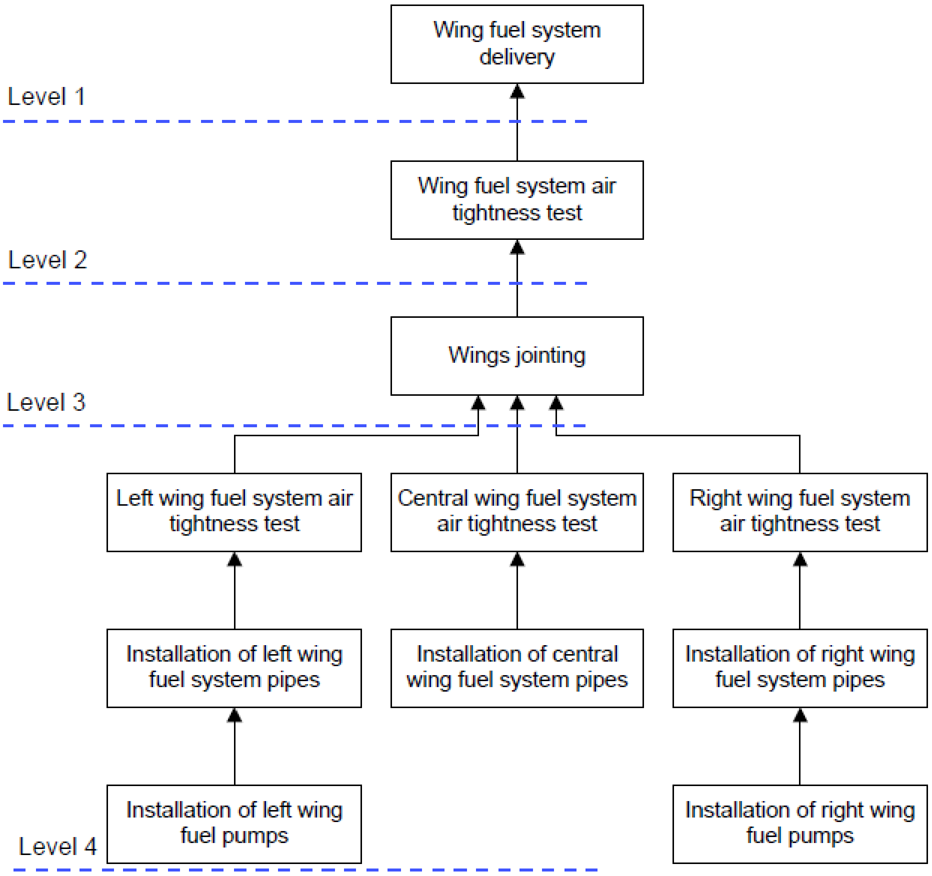


Figure 4-19 Proposed Work Breakdown Structure of Option 2

The main difference between the two options is the assembly process node level of fuel system parts installation. In option 2, fuel system parts installations belong to level 4 – system installation. While in option 1, these installations are in level 3 – big parts jointing and related installation.

What should be noticed is the difference of system air tightness tests between the two options. One wing fuel system air tightness test is planned to check all the fuel pipes at one time. In contrast, three sub air tightness tests are arranged before the final test after wing jointing.

4.3.3 Assembly Simulation

As discussed before, the fuel system of Flying Crane airliner is in a relative open environment with low structure constraint. This particular situation makes the flexibility of assembly process design. There are different approaches to fit the assembly task.

- Install pipes from one side to another side. For instance, install pipes from front inner wing spar to central wing rib.
- Install pipes starting at both sides. For instance, pipes installations start at both front inner wing spar side and central wing rib.

Actually, more flexibility is found in the assembly process design. When installing pipes, it is possible for layout all the pipes first, and then fasten the bolts of supports after connecting pipe connectors. Optionally, fastening can be done when install each fuel pipe.

The right wing fuel system assembly based on process option 2 will be considered as an example to illustrate one of the assembly approaches in 3-D environment. More assembly simulation details refer to Appendix C.

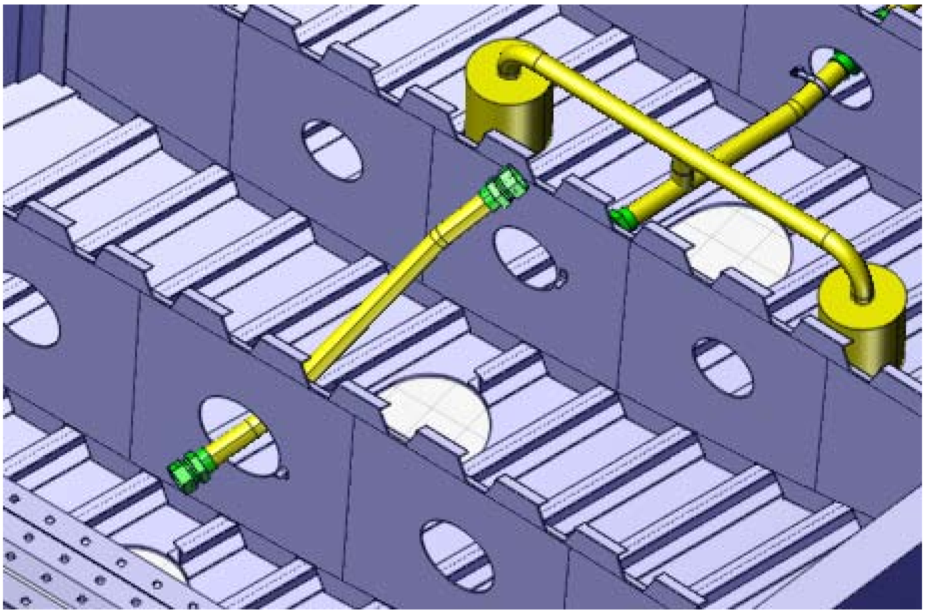


Figure 4-20 Assembly Simulation of Right Wing Fuel System Pipes

Due to the low assembly constraints of this case study, no system parts assembly problems are found in the simulation process.

4.3.4 Selection of Process Options

One of the advantages of 3-D assembly simulation is the capacity to find out both potential product design and process design problems in visual environment. Although no product assembly problems are found in this case study, process design still benefits a lot from the visual environment to choose the final process option.

The figure below illustrates the access panels on the lower aerofoil used for system installation.

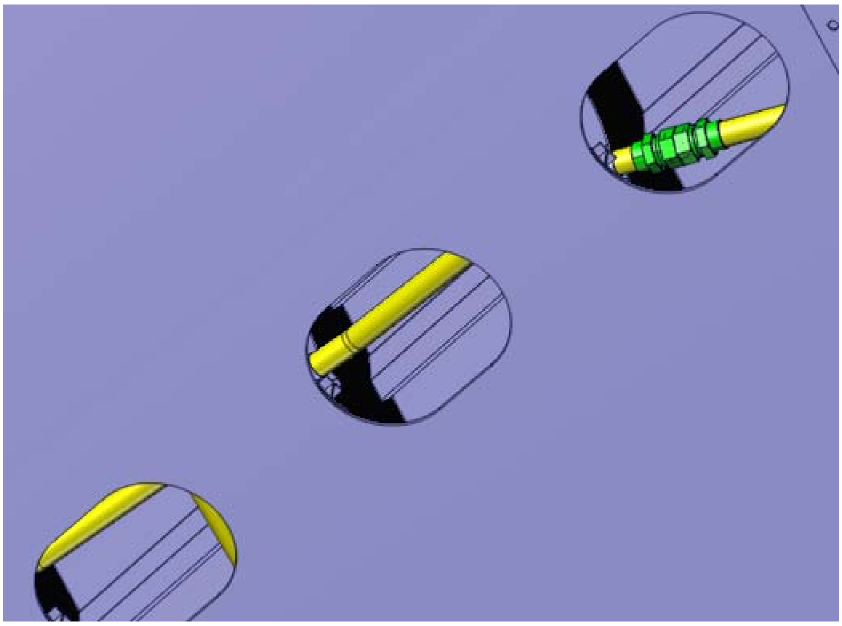


Figure 4-21 Access Panels on the Lower Aerofoil

In option 1, system installations take place after wings jointing. All the system parts have to locate through these access panels. Obviously, it is more difficult to install system parts than option 2, because upper aerofoil is covered after system installation and sub system air tightness test. Plenty of space is available for system assembly in option 2. In addition, there is only one air tightness test of whole wing fuel system due to the limited space for connecting test equipments for sub air tightness test. If leaks are detected through the whole system test, it is difficult to locate the leaking point as well as to reseal it. Therefore option 1 is more reasonable for wing fuel system assembly.

4.3.5 Produce Detailed 3-D Assembly Plans

3DVIA Composer provides a powerful annotation function both in 2-D text and 3-D labels. Since much of the assembly information is represented in 3-D graphic environment, 3-D assembly plans simplify assembly description significantly. Parts feeding information and special assembly note are the main textual carrier in 3-D plans.

The figure below illustrates the detailed 3-D assembly plan of installation of right wing fuel system pipes. This 3-D plan is based on previous simulation results.

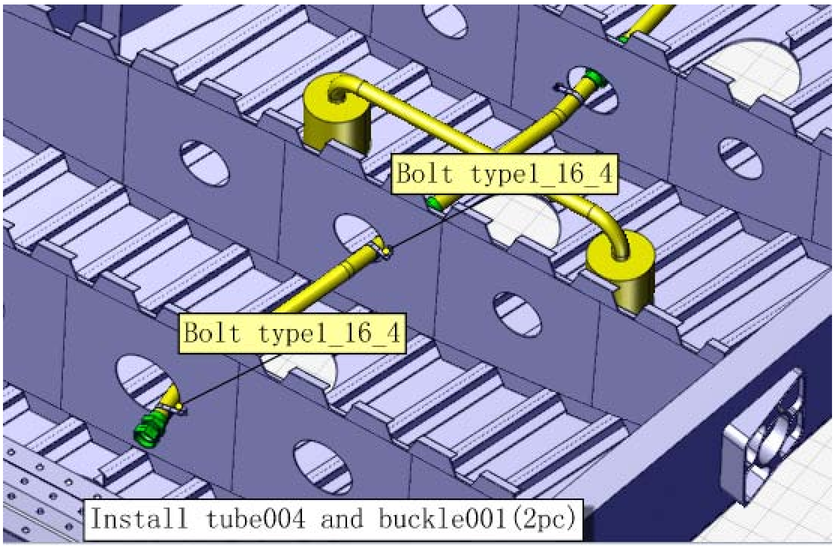


Figure 4-22 Detailed 3-D Assembly Plans in 3DVIA Environment

The author has made both the assembly movie and interactive real time assembly 3-D plan. The movie produce and 3-D assembly plan refers to Appendix E.

4.3.6 Initial Conclusion of Detailed Design Case Study 1

Initial conclusion can be made from this case study that in the ideal environment of low assembly constraints, the main issue is the different states of assembly environment which would lead to difficulty of accessibility and system functional test issues. Although few assembly problems can be detected through assembly simulation at this situation, it is very helpful for analysing the process design strategies to prevent potential process design problems.

4.4 Detailed Design Case Study 2

Detailed design case study 2 is grounded on AVD A-8 ECS. A-8 Hummingbird airliner is a fuel efficient propeller-powered aircraft designed by fulltime Aerospace Vehicle Design (AVD) students [48]. This case study is considered to be the most representative one of typical assembly environment, since kinds of system parts are arranged in a limited space making it high assembly constraint and more realistic compared to real assembly. Besides, the initial consideration is to select a typical assembly consist of different systems' parts including pipes, finished products and cable harnesses installation. However, after the search of previous projects, few models of aircraft system can achieve this requirement. Making appropriate adaptations of this requirement, the sub systems of ECS in this case can be treated as different systems.

4.4.1 Detailed Geometry Modelling

The original detailed CATIA models of ECS are designed by AVD students. The author obtained the data from Dr. Helen Lockett who is the author's supervisor.

The figure below shows the original CAD data in CATIA environment.

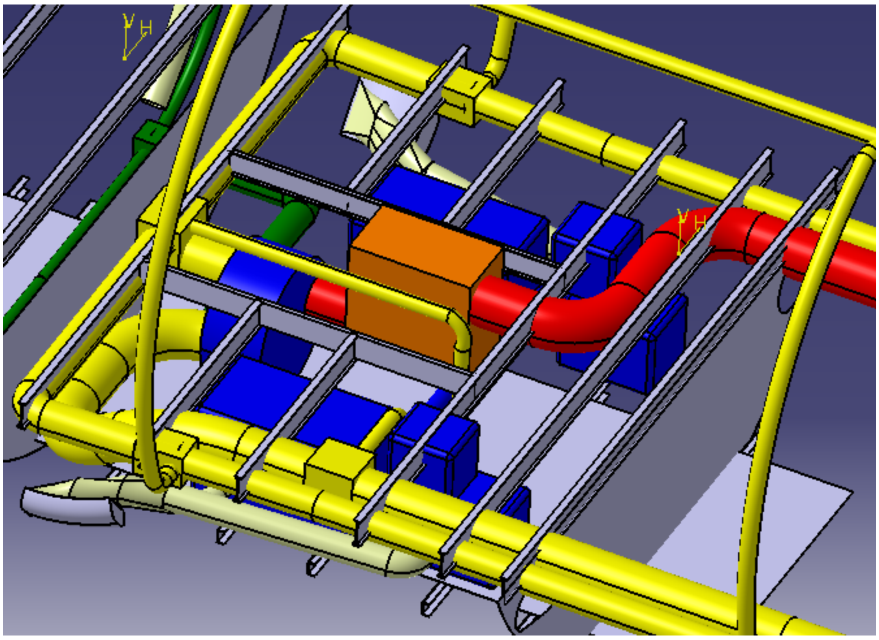


Figure 4-23 Original ECS Models from Detail Design Phase

A lot of assembly design problems are found when importing the forward fuselage structures. In the original modelling, some finished products (ECS packs with blue colour in the original models) are located outside the range of floor.

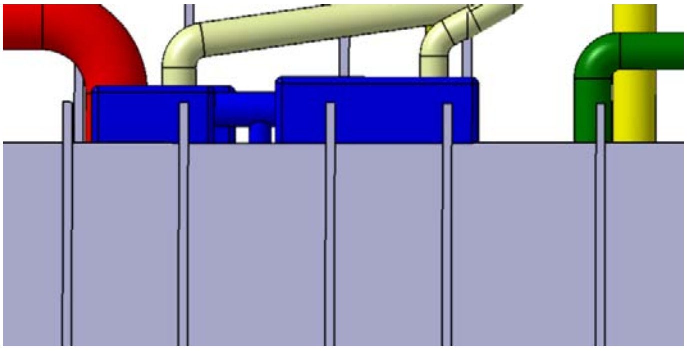


Figure 4-24 Location Problems of ECS Packs (Bottom View)

Collision and interference problems are found on pipes, ECS packs and beams.

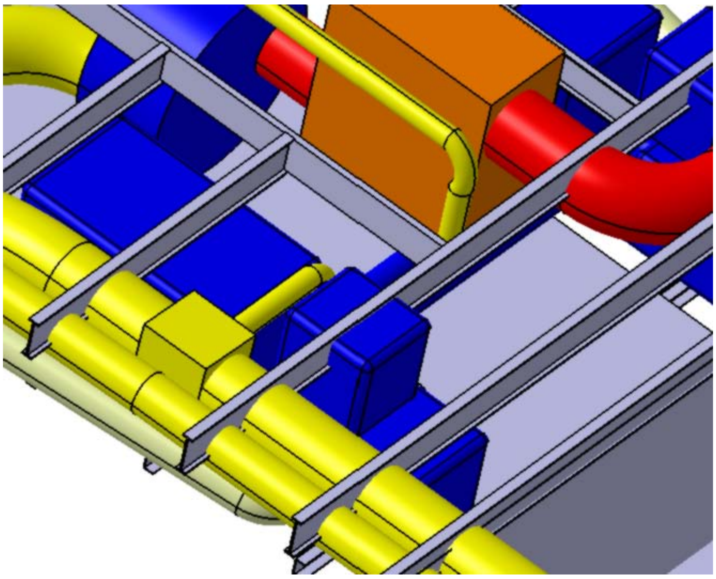


Figure 4-25 Interference Problems between System and Structure

No detailed assembly information including connections of separated pipes is found in the original design. A large amount of work in modelling has to be done to solve the problems of original design and meet the case study requirement. These modelling works are listed as below.

- Limitation of modelling in the bay.
- Adjustment of ECS packs location to fit in the range of floor.
- Adjustment of ECS packs location to solve interference problems.
- Adjustment of pipes location to solve interference problems.
- Adjustment of some pipes location to improve accessibility.
- Individual pipe definition including end style.
- Added supports and brackets for ECS packs and pipes.
- Added system assembly information including connection and fastening.

The result of redesign is shown as below. The detailed modelling process and application of DFA method can be found in Appendix D - Case Study 2 Detailed Modelling and Simulation.

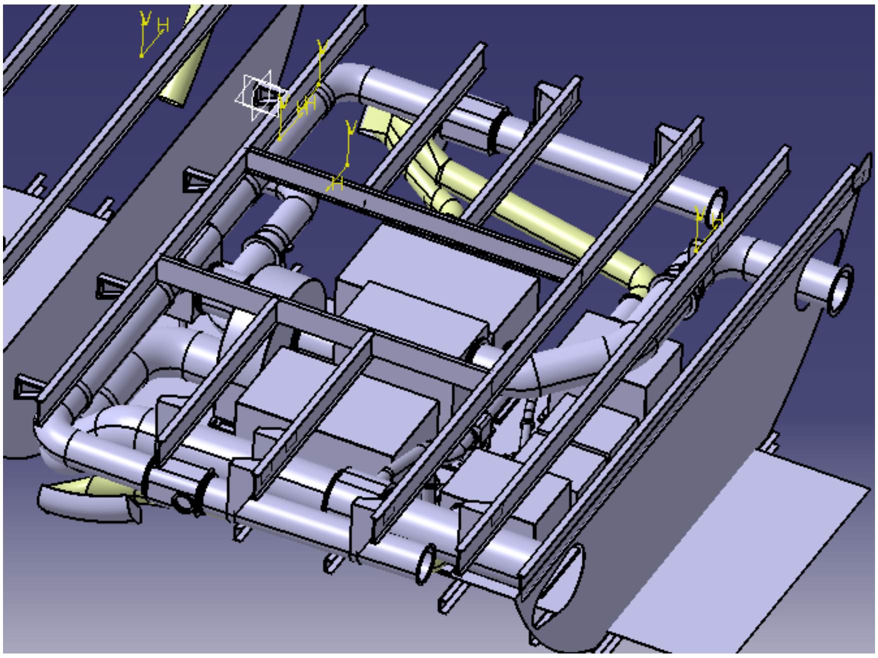


Figure 4-26 ECS Models after Redesign

It can be seen from the figure above, all the ECS parts in the bay has been modelled in details including parts arrangement, connections, fastenings and end style of parts. It should be noticed that the system modelling is on the assumption that structure models are froze. While in the practical engineering, both of system and structure design are in the iterative process applying concurrent engineering method.

4.4.2 Propose Process Options

Process options are limited in manufacturing of one company which is the same as detailed case study 1. Before the process options proposition, it is necessary to analyse the installation of ECS first to get familiar with states of assembly environment.

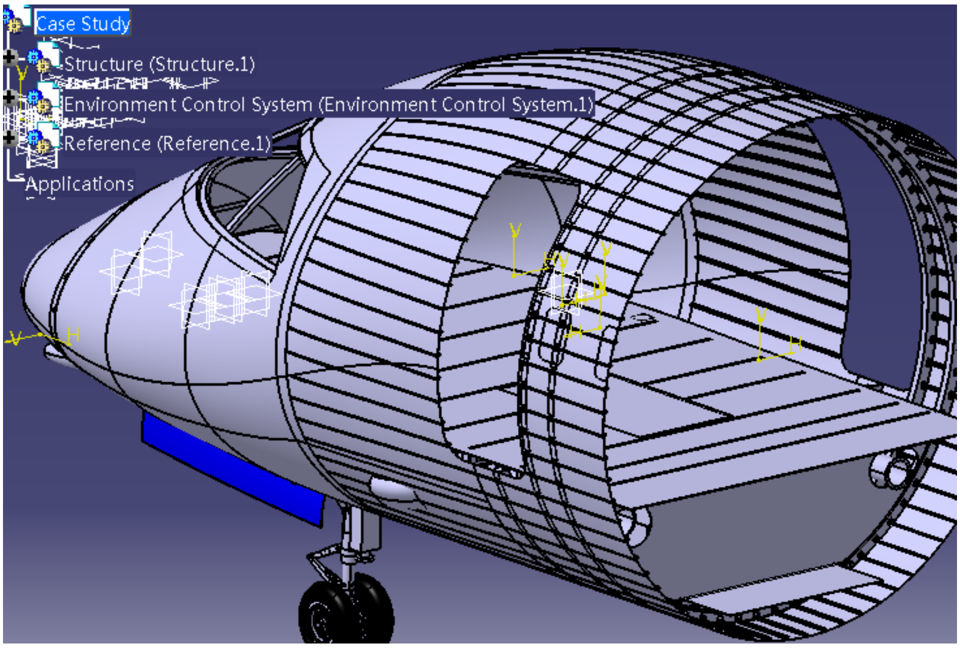


Figure 4-27 Assembly Environment of Detailed Case Study 2

The figure above shows the bay location and external assembly environment of this case study. The ECS bay is located among two separations, coverings, cross sections and cabin floor. There is an access panel on the floor designed for system maintenance. Since external coverings are directly riveted on cross sections and ECS pipes of large diameter are installed near each side of bay, it is not suitable to adding extra demountable covers used for system installation. Thus, the general process options can be formulated by access panel and cabin floor.

- Install the cabin floor first. All the system assembly activities use the access panel.
- Install the cabin floor later after the system assembly activities. ECS parts can access through the beams for installation.

The final assembly process node level of A-8 ECS is level 4, since all these assemblies are system installations and related assemblies. The brief work breakdown structure is described as below.

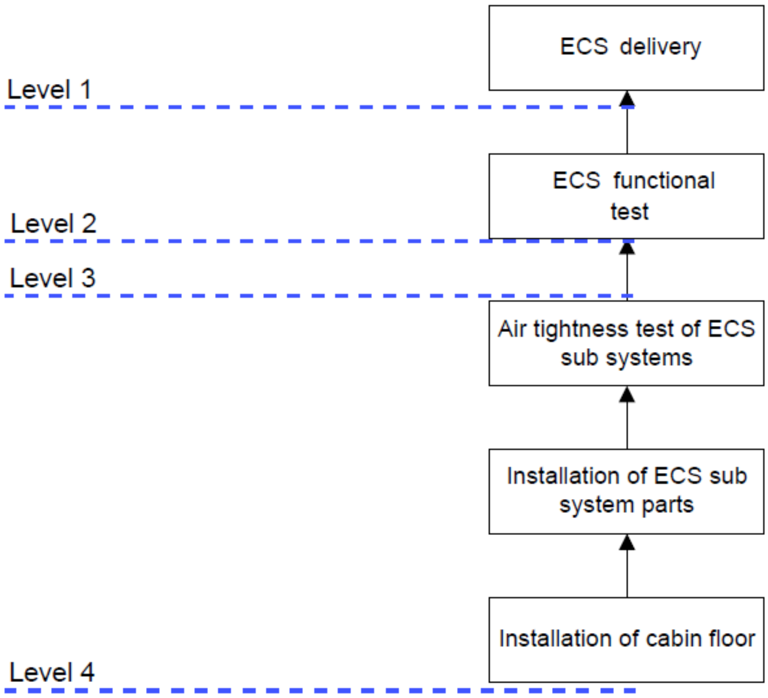


Figure 4-28 Brief Work Breakdown Structure of Option 1

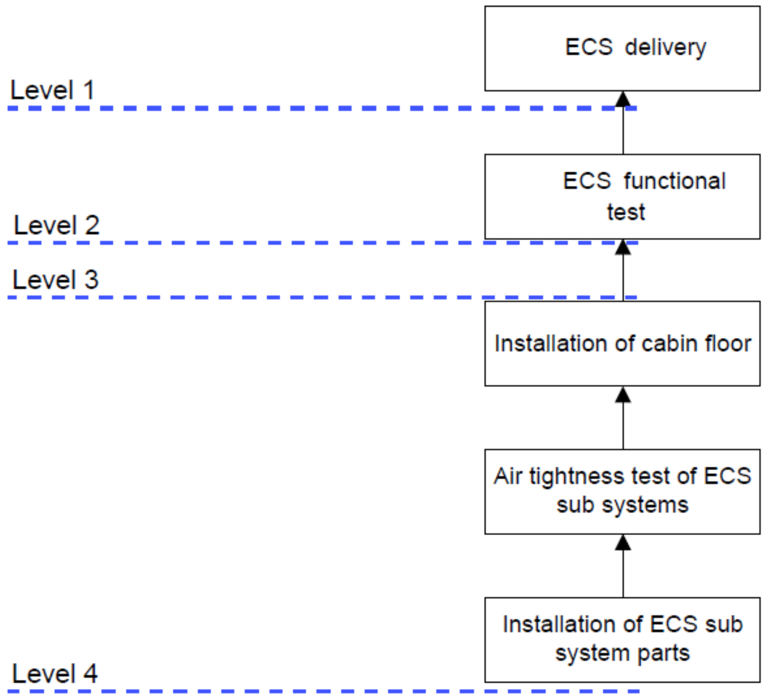


Figure 4-29 Brief Work Breakdown Structure of Option 2

It can be seen from the brief work breakdown structures of the two options, the module of sub system installations need to be expand based on certain assembly sequence. Hence, the main concern of process design in this case study is how to generate the installation sequence of finished products, pipes and other system parts.

4.4.3 Assembly Simulation

According to the process options, the assembly process design constraint is whether the cabin floor is installed before system installation. Because of the complicated of system layout, the assembly simulation is considered as an approach to generate the installation sequence of system parts.

Since the assembly simulation is done by disassembling (uninstalling) components from their final installed position, the simulation should follow the principle of minimum location distance and maximal accessibility when doing disassembly path planning. The simulation strategies for the two options are list below.

- Option 1: All system parts go through the access panel. The nearest system parts to the access panel will be disassembled first to gain more space for rest disassembly.
- Option 2: All system parts can access through both access panel and the space between beams where cabin floor is located. Simulation will follow the principle of disassembling the easiest part first to try to meet minimum task time.

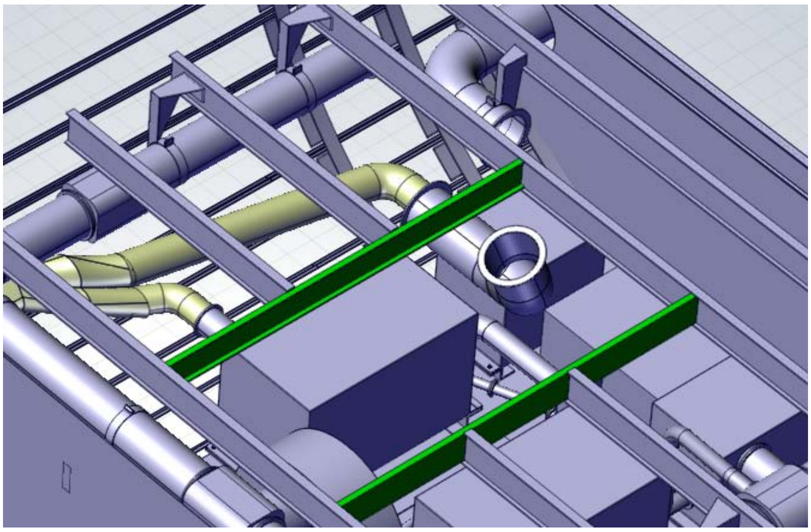


Figure 4-30 Assembly Simulation of Option 1

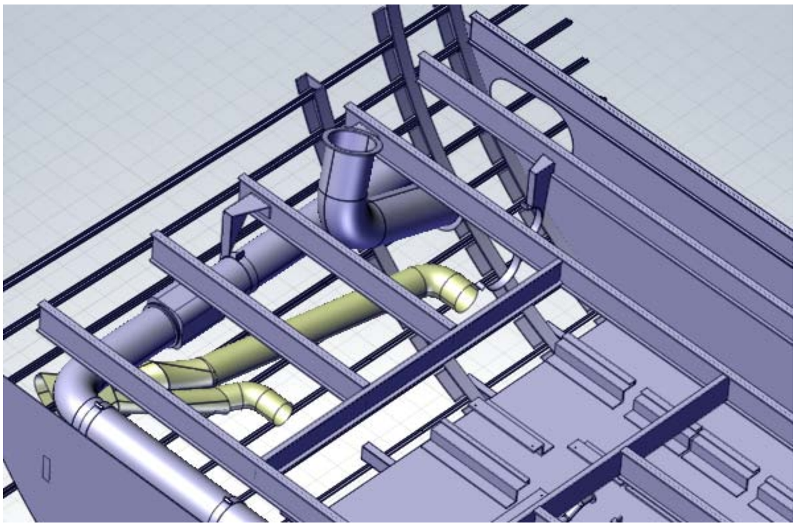


Figure 4-31 Assembly Simulation of Option 2

The assembly simulations of the two options are shown as above. More assembly simulation process details refer to Appendix D.

Although the author is both the product and process designer in the research, some product design problems are still detected in the assembly simulation. The figure below illustrates the collision problem when installing a pipe to the support.

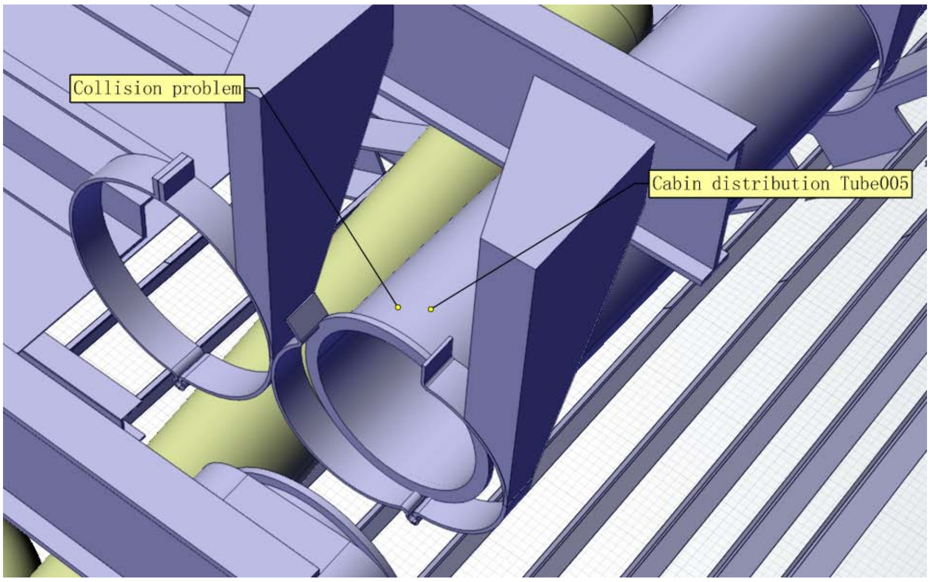


Figure 4-32 Design Problems Detected in Assembly Simulation

The pipe cannot access through the clamping band of the support, because the clamping band cannot be fully opened. The support arm will be redesigned to solve the problem.

4.4.4 Selection of Process Options

A common standard is set up for comparison of the assembly simulation results. Number of system parts' moves with different assembly path is compared in the table. Each parallel, rotating, upward and downward motion is defined as one move in the assembly simulation.

Table 4-3 Comparison of Number of Moves

No	Name of Part	Option 1 (access panel)	Option 2 (no cabin floor)
1	ECS Packs Tube006	2	2
2	ECS Packs Tube001	2	2
3	Cabin Distribution Tube009	2	1
4	ECS Packs Tube007	3	2
5	ECS Packs Tube002	3	2
6	Cabin Recirculation Tube003	3	4
7	Cabin Distribution Tube007	3	4
8	Cabin Distribution Coupling003	2	3
9	Cabin Distribution Tube006	4	4
10	Flight Deck Distribution Tube002	4	2
11	Cabin Distribution Tube010	3	3
12	Cabin Distribution Coupling004	2	1
13	Cabin Distribution Tube005	4	4
14	Cabin Distribution Coupling002	3	3
15	Cabin Distribution Tube004	5	5
	Total Moves	45 Moves	42 Moves

In this moves comparison, option 2 (no cabin floor) only takes an advantage of 6.67% than option 1(access panel). However, if take the total length of moving path into account, it is obvious to find that option 2 has a much shorter length than option 1. In addition, option 2 has much better accessibility and visibility than option 1. Thus, the general comparison of assembly time can be evaluated by the factors discussed before. Considering the simulation results and design constraints mentioned before, process option 2 is more reasonable.

In this case study, the recommendation process is option 2. Nevertheless, in practical process design the selection of options may change to option 1 if cargo and cabin air tightness tests are taken into account.

4.4.5 Produce Detailed 3-D Assembly Plans

The process design of A-8 ECS bay is quite different from the wing fuel system of Flying Crane because of the high complexity of the installation. According to the simulation result, the work breakdown structure can be expanded by adding sub system installation sequence.

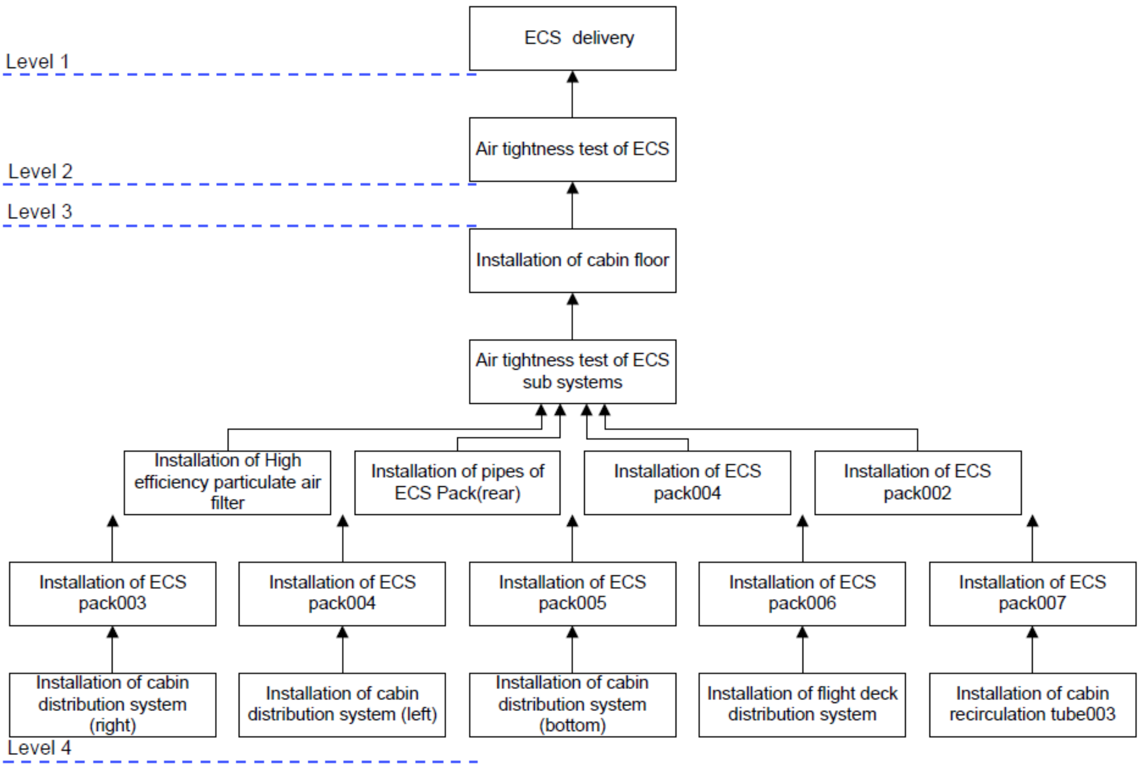


Figure 4-33 Detailed Work Breakdown Structure of Option 2

The figure above shows the detailed work breakdown structure of option 2. There are three rows of sub assembly which describe the assembly sequences. Modules in the same row can work at the same time.

Detailed assembly plans will be produced based on the work breakdown structure representing in pure 3-D environment in 3DVIA CAD system.

4.4.6 Initial Conclusion of Detailed Design Case Study 2

The detailed design case study 2 can be concluded that in the high assembly constraints environment, how to obtain the assembly sequence of sub system is the main concern of process design. This case study illustrates an integrated approach to gain the sequence by applying assembly simulation, analysing assembly states and considering the requirement of related test.

4.5 Summary of Chapter

This chapter has described the application of research methodologies in different design phase. Three cases including two detailed design cases have been studied to make initial conclusions.

In conceptual design phase, abstract DFA principle is used to propose assembly geometry of aircraft system. This proposed geometry of FW-11 fuel system has greatly helped the selection of process definition which is one of the main concerns in early process design.

The Flying Crane and AVD A-8 case present two typical aircraft system assembly situations respectively. Both of the two cases can be learnt from that assembly states are crucial for process design while assembly simulation helps process engineers to produce the reasonable process plans based on better understanding of assembly.

The AVD A-8 case is considered as a more common case can be found in practical assembly. Assembly simulation combined with assembly states analysis and system test consideration is found as the approach to gain the system assembly sequence through this case study.

The next chapter will propose an application system for detailed 3-D process plans, especially for the usage in shop floors.

5 Proposed Assembly Process Planning System

5.1 Introduction

Previous literature review shows that although assembly simulation has been applied in aircraft industry for some time, most of companies still considered it as an isolated assistant method of assembly pre-planning instead of involving it in a pure 3-D process design environment. Assembly plans are still described in text-based documents despite efforts have been done on document digitization. Since the management of CAPP input and output is a part of the research, it is necessary to develop a digital process planning system in pure 3-D environment.

In this chapter, the system input and output will be developed first after investigation of general system requirement. Then, a proposed 3-D process planning system will be introduced. Finally, a detailed customized application for shop floor usage will be developed, which is based on 3DVIA lightweight CAD system.

5.2 Development of Process Planning System

5.2.1 System Input

The input of the developing system is based on the current text-based process planning system which introduced in chapter 3. The difference of the two systems is the different type of design source, which are 2-D drawings and 3-D DMUs. In digital engineering, 3-D DMU models are considered to be the main process design basis. Therefore, the inputs of 3-D process planning system should be changed correspondingly.

The figure below shows the input of 3-D assembly process planning system.

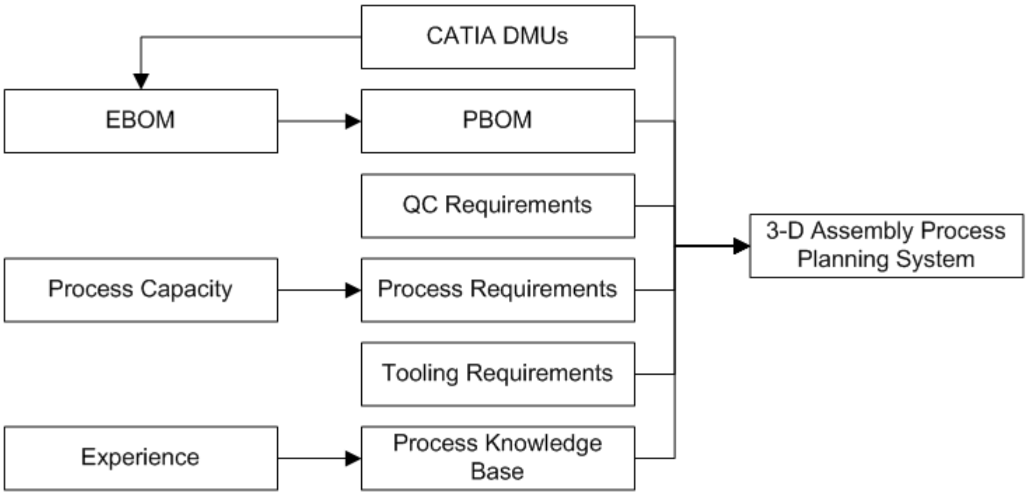


Figure 5-1 Input of 3-D Assembly Process Planning System

It can be seen that there are some other inputs of the system such as QC, process and tooling requirements. These modules are as important as product design data. However, since the research concentrates on how to reflex the demands of process design on product design, the main concern is what information should be included in the DMUs for manufacturing use when build the models. According to the literature review, this information is involved in PMI of DMUs. Thus, in the developing process planning system, the input of DMU models should contain PMI notations of crucial assembly geometric dimensions, assembly tolerance, system installation and test requirements, and Bill of Materials (BOM).

5.2.2 System Output

The tradition assembly process planning activities produce detailed text-base assembly instructions and parts feeding lists. The MBOM tree is then structured by the feeding information and sequence of assembly plans. The study of previous researches found the assembly instructions are described in textual documents. Some companies who have widely used assembly simulation method to help process planning, however, still produce process assembly instructions in text documents. That means process engineers have to double their works, since they should describe the assembly both in the 3-D simulation environment and textual instructions.

According to the two detailed case studies from chapter 4, assembly simulation results of 3DVIA system are managed in XML based smg format. Thus, the simulation results can be easily translated to 3-D process plans. The system output can be formulated as blow.

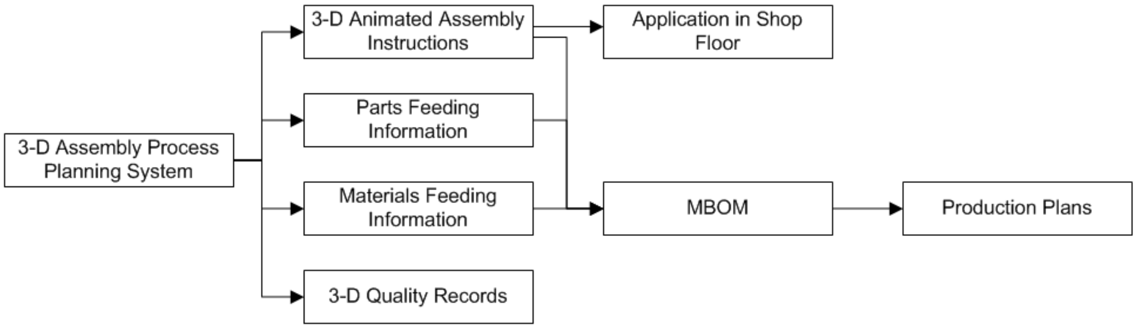


Figure 5-2 Output of 3-D Assembly Process Planning System

Since process plans also transfer quality control information in manufacturing process, 3-D quality records should also be considered as the one of the system outputs though this is out of the research scope.

5.3 Integration of the Process Planning System

5.3.1 Integration of 3DVIA into Process Planning System

Previous research has found some lightweight CAD data can inherit the information needed for process design from raw CAD data. For assembly task, lightweight CAD data do not have influence on the understanding of raw models. In this project, the developing system is based on 3DVIA system.

Generally, the proposed system should transfer process information among three layers which are design interface layer, process data layer and CAD system layer.

The figure below illustrates the concept of the system. It can be seen from the activity diagram that 3DVIA system is fully integrated in the process planning activities.

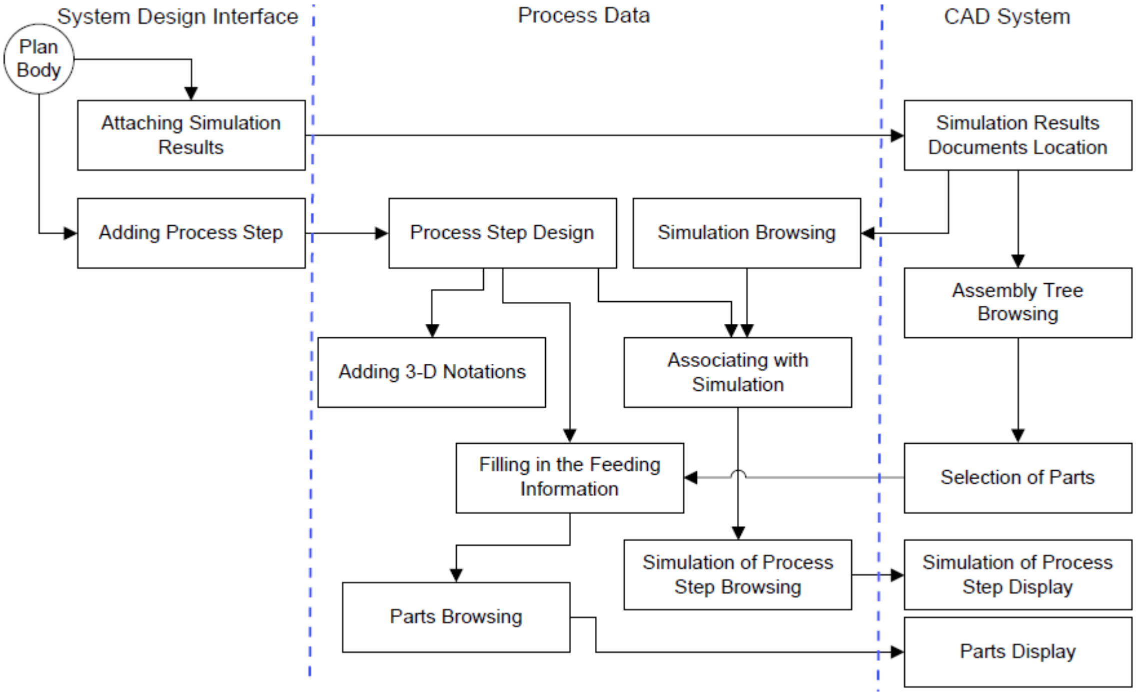


Figure 5-3 Activity Diagram of the Process Planning System

5.3.2 Integration with PDM Systems

The proposed assembly process planning system in this research is one kind of CAPP system. The figure below illustrates how CAPP links other product development systems in modern manufacturing enterprise.

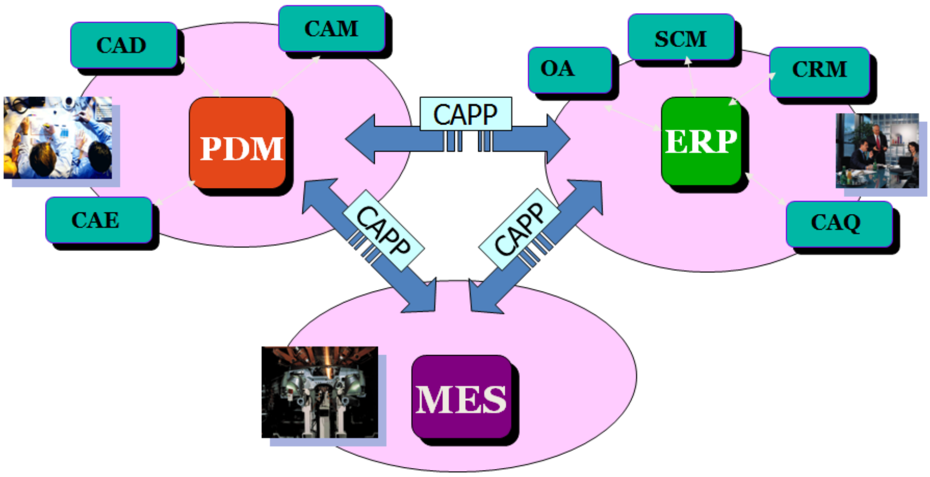


Figure 5-4 CAPP in Manufacturing Industry [42]

In this framework, CAPP is the junction of other three systems which means any developing process planning system should consider the integration of other systems. Thus, with limitation of this research scope, the developing system should closely integrate with PDM. The system function includes:

- Product CAD data importing
- Retrieving and obtaining BOM information
- Retrieving and obtaining tooling information
- Change management of 3-D process plans
- Configuration control of 3-D process plans

5.4 Application of System in Shop Floor

5.4.1 Publication of Simulation Results to Shop Floor

The process planning system takes 3DVIA as the core application system. After the process design, 3DVIA Composer provides the function of exporting assembly results into interactive 3-D documents by setting the document right manager.

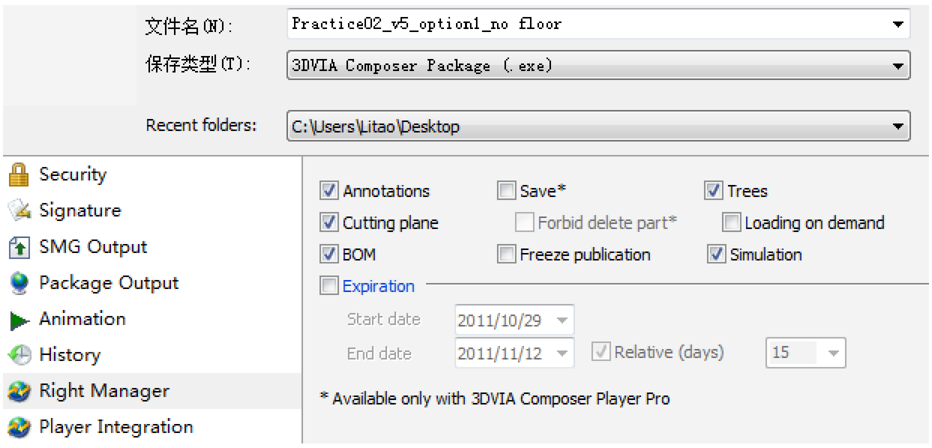


Figure 5-5 Right Manager Settings of 3-D Process Plans

Users in shop floor can play the 3-D process plan in real time to guide the assembly work. The figure below demonstrates the 3-D documents of installation of Flying Crane right wing fuel pipes using 3DVIA Player tool.

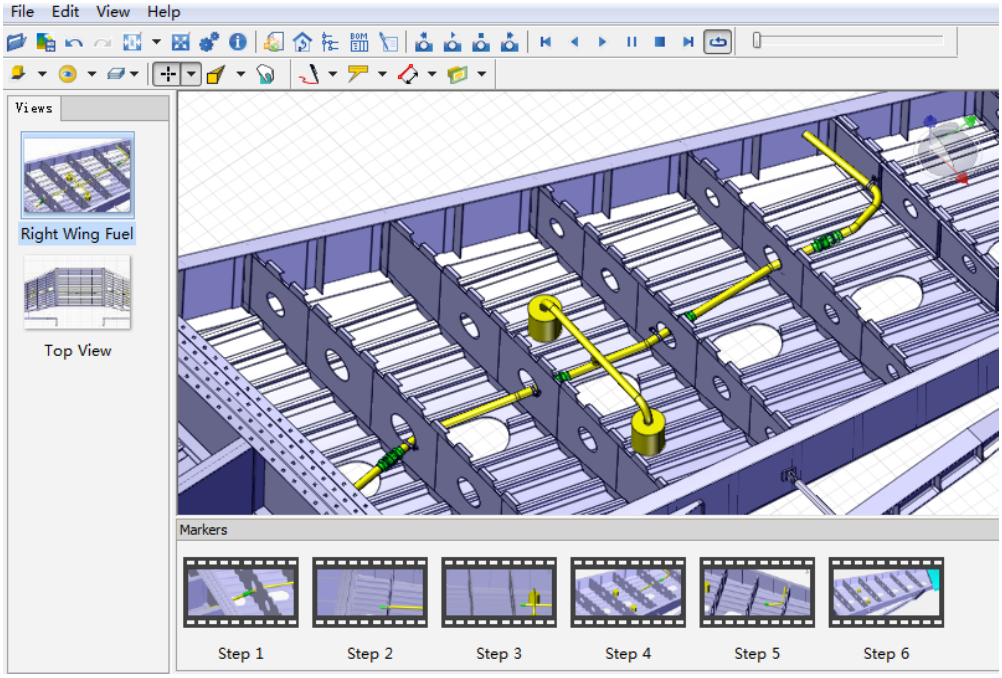


Figure 5-6 3-D Assembly Process Plans Playing in 3DVIA Player Tool

5.4.2 Algorithm for Customized Application

As mentioned before in chapter 4, assembly simulation is done by disassembling the installed product models. This method results the default playing sequence to be a disassembly process. It would not lead to problems in playing 3-D assembly process continuously, since 3DVIA player tool has the reverse playing function. However, as the figure shows above, process steps are defined as markers in the time line of 3DVIA Composer. When the user clicks the defined markers to play a selected process step, they would find the player tool cannot represent the process sequence in installation order. What is more, the player tool is an isolated programme with some basic functions. In most cases, there basic functions cannot fit all the specific situations, and therefore the application system should be customized to meet the requirement of different shop floor.

Since 3DVIA Composer supports secondary development, according to the study of 3DVIA player ActiveX Application Programming Interface (API) [43], the programme algorithm is illustrated in the following flow chart.

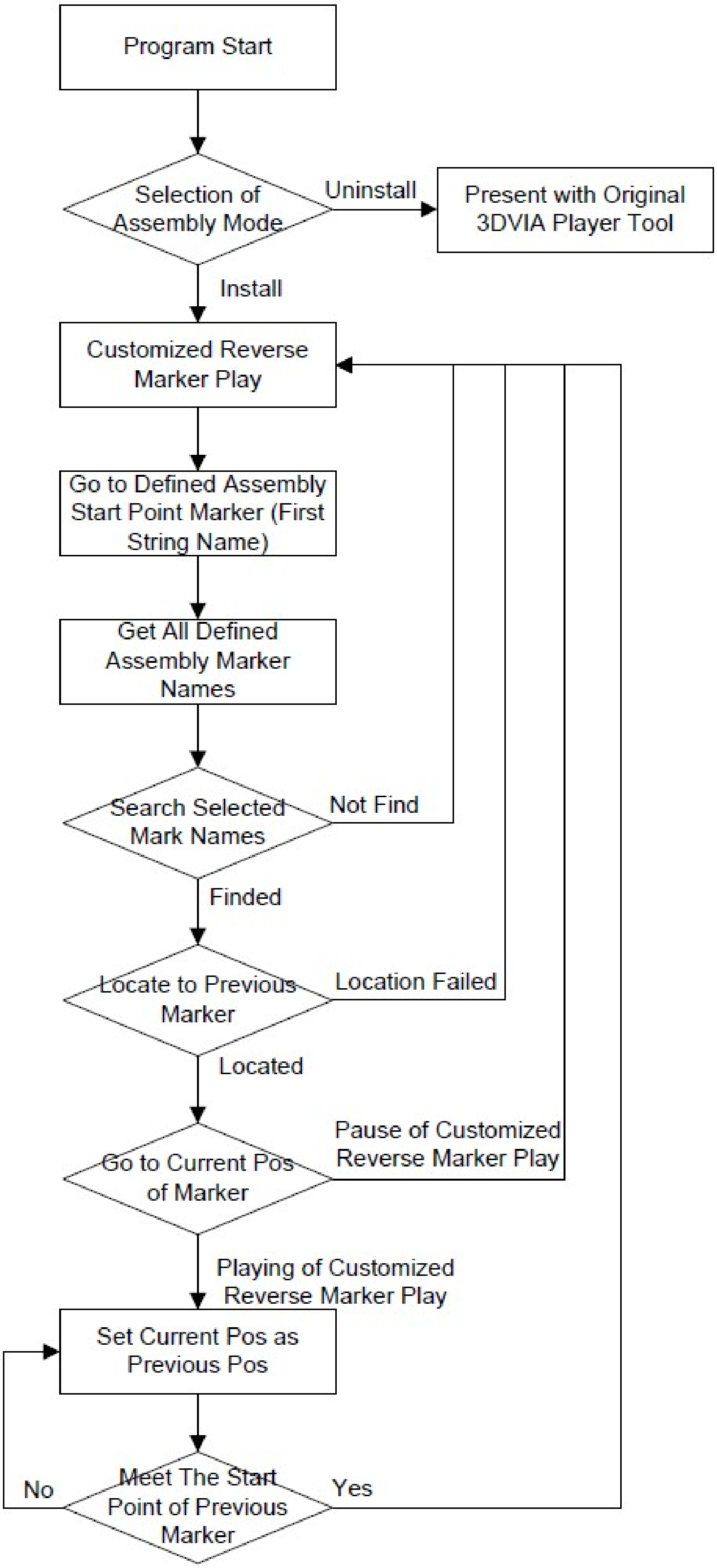


Figure 5-7 Programme Algorithm of Customized Reversed Marker Play

The main customized marker playing code is described as below:

Step 1: Use function GetAllMarkers( ) to find the strings of marker name of current simulation document.

Step 2: Use function GoToMarker( ) to locate the start marker from time line.

Step 3: Use function Pos( ) to set numerical value 1 as tolerance descending for current frame.

While (DS3DVIAPlayerActiveX1.Pos > 0)

{

DS3DVIAPlayerActiveX1.Pos = DS3DVIAPlayerActiveX1.Pos – 1 **(5-1)**

}

The figure below demonstrates the customized prototype application developed by the author with ActiveX and VBA programming.

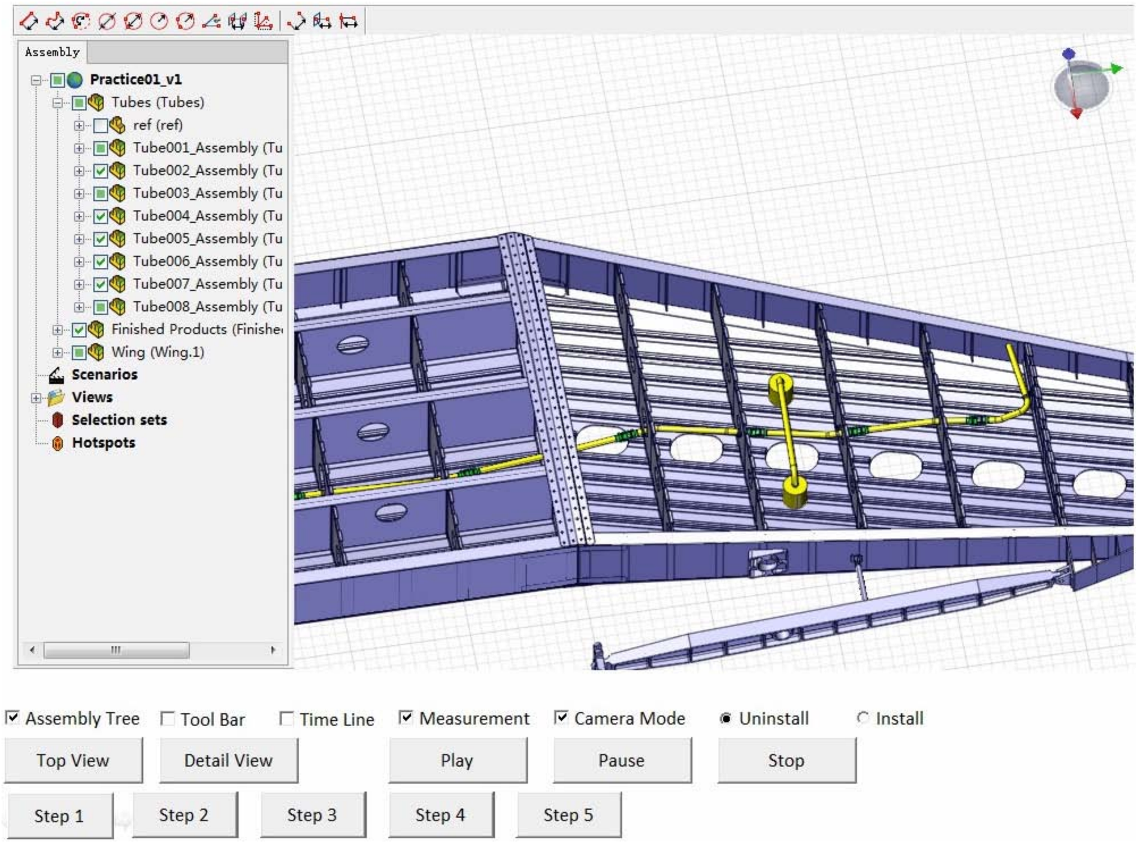


Figure 5-8 Customized Application

More details of Visual Basic for Applications (VBA) programming codes refer to Appendix E.

5.5 Summary of Chapter

This chapter states the input, output and integration of proposed 3-D assembly process planning system. A customized application of shop floor 3-D assembly representation is developed by the author using ActiveX and VBA programming.

6 Discussion and Conclusion

This chapter will summarize the results of the research. The findings of each research stage including previous gaps in literature, limitation of research methodology and case studies are then discussed. The particular advantages of lightweight CAD format are also discussed followed by recommendations for readers who intend to develop the assembly process system of aircraft system. Lastly, future research is described based on the discussion.

6.1 Discussion of Research

6.1.1 Gaps of Previous Literatures

Although many research of digital manufacturing has been carried out in recent twenty years, most of them concentrate on plant layout simulation, machining and aircraft structure assembly. Few literatures were found on assembly process design of aircraft systems. Since assembly process design is considered as an experience based activity in traditional view, researches related to this field require researchers having engineering background of assembly process design. Compared with structure assembly, system assembly is more specialised. The approach of obtaining system assembly sequence is not only decided by product assembly design itself, but also other aspects such as manufacturing capacity, system function test requirement, pilot operation requirement, QC requirement and the maintenance requirement of ground crew. This would possibly explain why few literatures are relevant to system assembly process design. Within the scope of research, an integration of approach which combines both product design and process design should be developed in concurrent engineering mode.

According to the investigation of CAPP system, the automatic assembly sequence calculation CAPP is found to be failed because of the high complexity of real assembly especially in aircraft industry. After that, assembly simulation is used as the main method to obtain assembly sequence. However, further research found many companies still consider assembly simulation as a tool of pre-plan, and describe the assembly process in textual format instead of fully involving the assembly design in the pure 3-D digital environment. In this research, a proposed assembly process planning system framework and the representation application of shop floor is developed later.

6.1.2 Research Methodology

Research methodologies are formulated according to the investigation of literature review. The success of the methodology is the application of abstract DFA principles in system assembly geometry design, while limitations are found in development of the research methodology of detail design phase.

In the early design phase, there are many aspects which would lead to the change of initial product design. This research focuses on how the early process design in the 3-D environment helps improving initial product design. Thus, the developed research methodology of early design is limited in product geometry. However, the research methodology of early design phase is still found hard to structure at the beginning of the research. In early design phase system design concentrates on system framework and performance calculation, product geometry of aircraft system is not considered due to the lack of sufficient calculation results. Abstract DFA principles solve the issue by proposing the initial system geometry for process design.

As introduced in chapter 3, DELMIA which provides a complete solution of digital manufacturing is the ideal software for this research. Although 3DVIA system is chosen as the process design software in this task due to the difficulty to access license of DELMIA in the university, some important function of DELMIA is irreplaceable. DELMIA and 3DVIA both have assembly simulation function which can be used to finish complicated assembly task. However, further research found that in comparison of different assembly process, 3DVIA system is hard to evaluate process options because of the lacking of assembly time and cost estimation. In contrast, other research [34] has applied the estimation of operation time and cost in DELMIA since it is the native support function.

6.1.3 Case Studies

Lessons are also learnt in many aspects drawn from the research results of three case studies from different design phase.

The research of FW-11 case is based on the GDP results and further research of fuel system. Hence, the main research activities should be taken place in late conceptual design phase. The research result of FW-11 fuel system case reveals the integrated approach of process design in a concurrent engineering environment. In this design process, results of early process design can be fed back to product design in time following by the changes of early product design. Comments may be made that this iterative process [28] takes much time in early design phase. It is true that more time will be taken in the process when process design factor is involved in early design phase. But considering the curve of cost of correcting errors in the life cycle chart which is introduced in chapter 2, it is an improvement of product that well worth the expense.

In chapter 3, the comparison of difference of DELMIA and 3DVIA reveals that lightweight CAD system cannot simulate cable harnesses assembly in real time. Additionally, due to the large amount of work in 3-D electrical cable harness modelling, the two chosen cases for detailed design phase only consider the installation of rigid parts. What is more, the assembly simulation of cable harness is much more challenging than rigid system parts. The assembly simulation of flexible parts is another research field. Thus, this limitation would affect the research result in some extent, since the proposed process design process may need to adjust.

The detailed cases only simulated the installation of system parts. While in real system installation, screw driver, tooling and other special facilities are used to help the assembling. The accessibility and assemblability of these things should also be considered and simulated in 3-D environment.

In comparison of the two process options of AVD-8 ECS bay systems, alternative method is found to solve the lacking of assembly time estimation in

3DVIA system. However, this method is considered as low efficiency. The counting of moves is done manually which is too subjective to meet digital process design requirement.

6.1.4 The Developing Process Planning System

In this research, 3DVIA system is chosen as core of the 3-D process planning system. Ignore the drawbacks of time and cost estimation of the software, 3DVIA provides a powerful technology illustration tool to produce 3-D process plans. It can be seen from the investigation of the current assembly process design in chapter 3 that assembly plan does not only mean assembly instructions in final assembly plant. There are other assembly related activities including system test, alignment and inspection operations which should also be considered as one of the assembly plans. However, it is difficult for DELMIA to provide these operation instructions. In this sense, 3DVIA system has the significant advantage compared with DELMIA.

When applying in shop floor, the main assembly instruction material of DELMIA is recorded AVI video files from DPM tool. Seriously, it cannot be treated as the digital assembly plans because the recorded video is only an animated instruction movie. Most of functionality is limited in the video player software itself. In contrast, 3DVIA provides both recorded AVI video and interactive assembly executable file. The workers in shop floor can simply open the interactive assembly plan which is produced by 3DVIA, and play the 3-D animation in real time. The most important of this interactive plan is once the animation is played, the worker can pause the playing if necessary, and have a more detailed customized view if the user demands. This user operation will not edit any CAD content. Also, the given 3DVIA CAD data can be automatically update according to a simply operation when the source is changed. More flexibility is found in the integration of website based PDM system due to the XML lightweight CAD format of 3DVIA and ActiveX support.

6.2 Recommendations

Based on the research results and discussion, some recommendations are given below to the readers who are interested in applying the digital assembly process design for aircraft system.

- In early design phase, try to use abstract DFA principles to propose initial system geometry, and reflect the early assembly process design result to product design applying Fan's design mode [28].
- It is recommended to consider all the parts from different system in a bay or certain installation position as a basic unit to carry out the assembly simulation. The exact parts in the bay can be obtained from PDM system [32].
- Assembly simulation should be fully involved into the process planning system instead of considering it as a pre-plan tool.
- Both DELMIA and 3DVIA system can be used for assembly simulation. DELMIA has significant advantage in time and cost estimation while 3DVIA is dominant in 3-D technology illustrations.
- The interactive assembly plan of 3DVIA system is recommended for the application in shop floor.

6.3 Conclusion

The following is a summary of the conclusions of this research:

- A method to assist with process design for aircraft system assembly has been successfully developed and tested on three case studies. The three case studies approach an integrated method combined with product development philosophy, design for assembly principles and digital assembly technology which can be used to find out potential problems of both product and process design. Although the shortage of time and cost estimation is found in selection of optional process in 3DVIA system, the results of case studies have met the research aim generally.

- The method can be applied at the early and late design stage. In the early design stage, abstract DFA principle is used to propose the initial system assembly geometry to consider as the basis for early assembly process design. In the late design stage, assembly simulation is used to help process option chosen and get the sub-assembly sequence to produce work breakdown structure.
- The method fills a gap in previous research which does not address systems assembly. This contribution to knowledge allows further research of integrated assembly system including aircraft structure and system to be taken place based on this research results.
- The benefits of using a 3-D process planning system on the shop floor have been demonstrated. The real time running interactive 3-D representation makes the assembly process plans more visible and easy understanding to operators in assembly plant. The XML based lightweight CAD data system shows the advantage when integrating with CAPP and PDM system.

6.4 Future Work

Specific areas for future research are described below:

- To demonstrate the integration of PMI into CATIA system and the application in digital process design.
- To illustrate how 3DVIA lightweight CAD system represent technology illustrations in terms of system test, alignment and inspection.
- To apply other method to estimate assembly time. For instance, the time calculation method for electronic systems and equipments provided in MIL-HDBK-472 the Maintainability Prediction of Military Standardization Handbook since assembly has closed relationship to maintenance.
- Research how to involve QC requirement into 3-D assembly plans.
- Research how to integrate DELMIA and 3DVIA in the digital process design process to benefit the advantages of the two CAD systems.

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APPENDICES

Appendix A FW-11 GDP Contributions

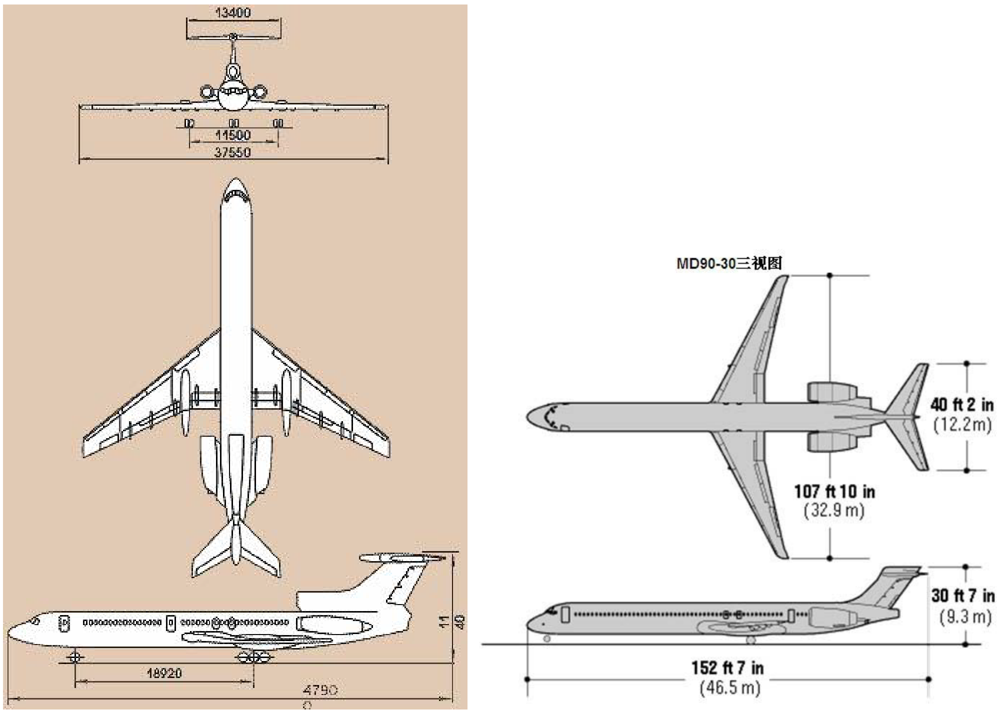
A.1 Introduction

Within different three phases of FW-11 project, the author was involved in geometric design characteristics, family issues and design constraints, cabin layout & family issues team. In preparing the GDP final presentation stage, the author was in charge of the video produce. The first two teams are in design phase I, cabin layout & family issues team is both in design phase II and III.

A.2 Geometric Design Characteristics (Phase I)

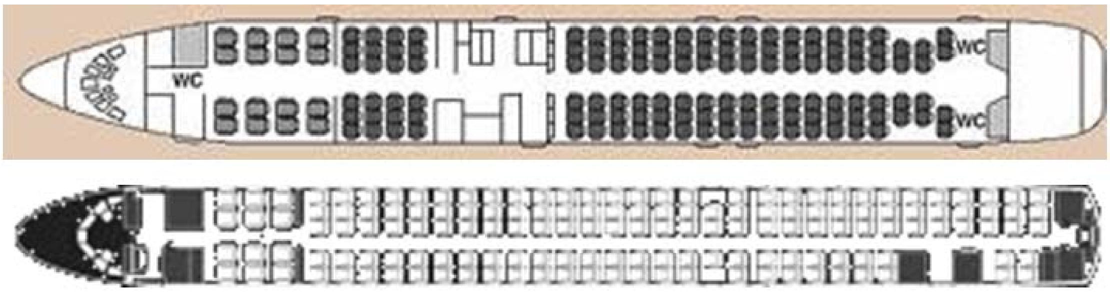
This task is collect general geometric data from existing 150 to 250 seats aircraft according published information. The main aims are comprehensive survey of the geometric characteristics, controls (ailerons, tail plane, elevator, rudder, flaps, spoiler, and airfoil sections), systems (airframe and avionics), structures and materials. It was divided into four groups of aircraft, Boeing families, Airbus families, Flying wing aircraft and other airliners.

The author investigated the group of others airliners, and considered Tupolev Tu-154M and MD-90-30 as typical examples. The two figures below illustrate the geometric data and cabin layouts of the two airliners.



Tupolev Tu-154M MD-90-30

Figure A-1 Three Views



Tupolev Tu-154M (upper) MD-90-30 (lower)

Figure A-2 Cabin Layouts

In the initial design stage, family series development and passenger comfort had been noticed according to data survey result. Long pitch and good seats configuration like 2-2 (one aisle) and 2-4-2 (two aisles) contribute more to passenger comfort.

A.3 Family Issues and Design Constraints (Phase I)

This task consists two parts which are family issues and design constraints. The latter part which is the author's research part, mainly concentrates on additional design constraints that need to be considered in the requirements compared with design drive group. Following by this guideline, top level requirements and something becoming the major design focus recently should be considered firstly.

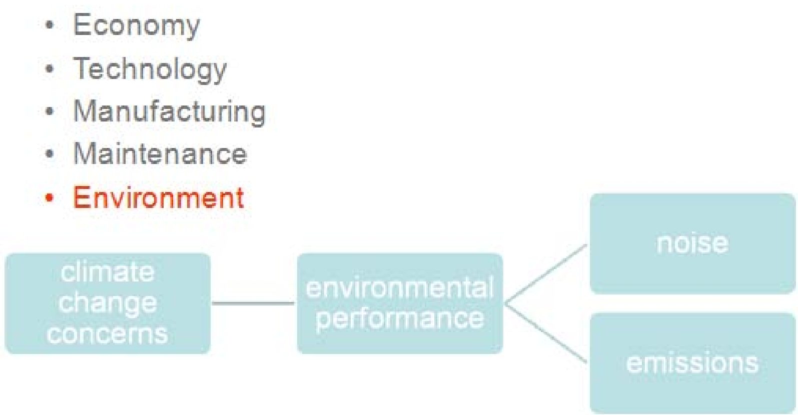


Figure A-3 Additional Design Constraints Concerns

Noise and emissions are two recent problems that causing industry's concerns. Airbus and Boeing have taken actions when they are developing a new general airliner such as A380 and Boeing 787. FW-11 project is aiming a 20.5 EPNdB noise reduction in 2018, and 23.0 EPNdB in 2028 [49].

A.4 Cabin Layout & Family Issues (Phase II and III)

A.4.1 Design Process

The design method of cabin layout in phase II conventional baseline and phase III flying wing approach is different. In phase II, the input information for cabin arrangement is market analysis and strategy of AVIC. Based on this requirement, cabin layout is the first design stage in the process. That means the baseline geometric data is determined by the cabin layout result. Other groups use the result to calculate CG, performance, aerodynamic, etc.

When it comes to phase III, because of the particularity of flying wing, aerodynamic efficiency and geometry results become the basic input of initial cabin layout design. The cabin arrangement work in this design process is to validate whether the proposed geometry data meets the requirement of cabin. If not, the geometry data should adjust and recalculate the aerodynamic, then arrange the cabin to validate again. In phase III, this design cycle repeated times to compromise related aspects.

In family issues part, because of the manufacturing background of the author, general strategy of family development will be considered.

A.4.2 Cabin Layout of Baseline

Two baselines, medium and long range airliners are designed according to the requirement.

A.4.2.1 2-D Cabin Layout

Cabin arrangements are made in CATIA 2-D drawings first to define the geometry as basic information for other groups. The two figures below are the final arrangements of baseline airliners.

Figure A-4 Cabin Layout of Medium-range Airliner

Maximum seating capacity： 320 in all-economy class and high density configuration

Cabin arrangements are made in CATIA 2-D drawings first to define the geometry as basic information for other groups. The two figures below are the final arrangements of baseline airliners.

Table A-1 Three-class Cabin Configuration of Medium-range Airliner

Maximum seating capacity	320 in all-economy class and high density configuration
Typical configuration	230 in mixed class
External fuselage width	5.64m
Internal cabin width	5.30m
Seating abreast	8(2-4-2) for economy class
First class seats	12
First class pitch	85 in
Seat width	27 in
Business seats	35
Business pitch	60 in
Seat width	24 in
Economy seats	184
Economy pitch	32 in
Seat width	20.7 in

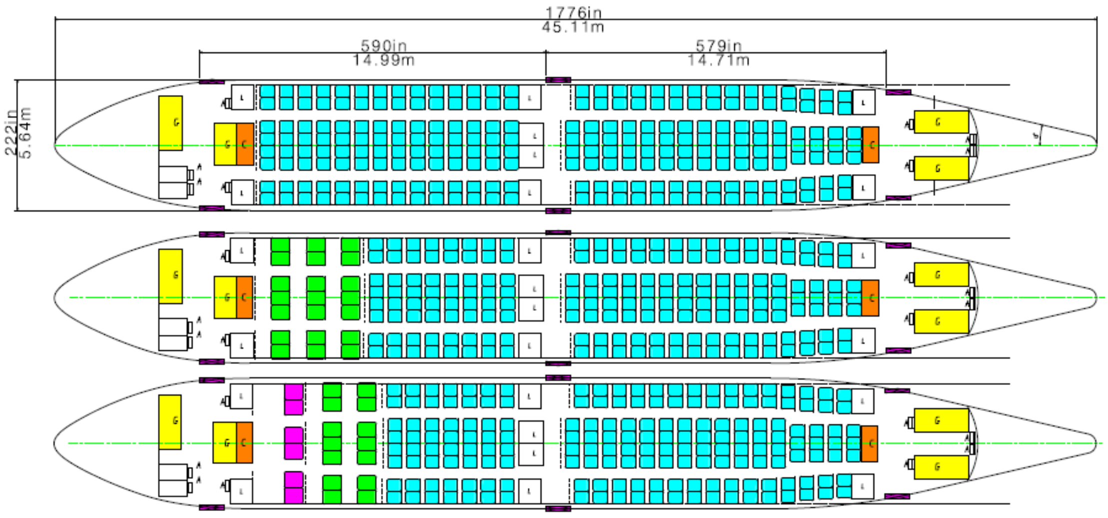


Figure A-5 Cabin Layout of Long-range Airliner

Table A-2 Three-class Cabin Configuration of Long-range Airliner

Maximum seating capacity	232 in all-economy class and high density configuration
Typical configuration	196 in mixed class
External fuselage width	5.64m
Internal cabin width	5.30m
Seating abreast	8(2-4-2) for economy class
First class seats	6
First class pitch	85 in
Seat width	27 in
Business seats	14
Business pitch	60 in
Seat width	24 in
Economy seats	176
Economy pitch	32 in
Seat width	20.7 in

The cross sections and side views illustrate the aisles dimension of three classes, also the cargo area.

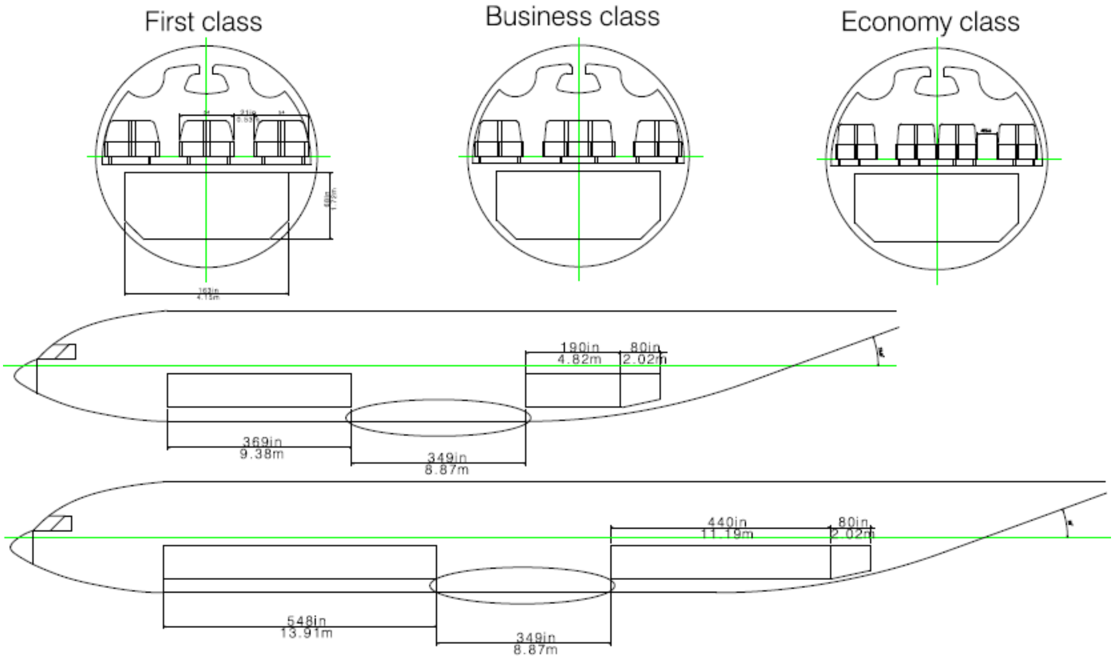


Figure A-6 Cross Sections and Side Views

According to the definition of cargo area, cargo capacity can be calculated. LD3 standard container is chosen as the typical cargo configuration.

Table A-3 Cargo Capacity

	Long range 232-seats		**Medium range 320-seats**	
Cargo area	FWD	AFT	FWD	AFT
LD3 Containers (No.)	12	6	18	14
Container cargo (m^3)	81		144	
Bulk cargo (m^3)	9.85		9.85	
Overall cargo volume (m^3)	90.85		153.85	
Cargo/passenger(m^3)	0.39		0.48	

Followed by the airworthiness standard FAR/CS/CCAR part 25, part 709, part 783, doors and emergency exits are arranged as blow

Table A-4 Doors and Exits

	Long range 232-seats		**Medium range 320-seats**	
	Type	No. of	Type	No. of
Passenger/crew doors	A	4	A	6
Emergency exits	1	2	1	2
Cargo doors	N/A	2	N/A	2

Table A-5 Dimensions for All Doors and Exits

Passenger/crew doors	1930mm×1070mm (height by width)
Emergency exits	1660mm×1070mm (height by width)
Cargo doors	1700mm×2700mm (height by width)

A.4.2.2 3-D Cabin Layout

After the 2-D cabin arrangement drawings was finished, 3-D CAD models was built to illustrate the configuration in virtual environment. In this stage, some basic CATIA models like doors and different kinds of seats are made.

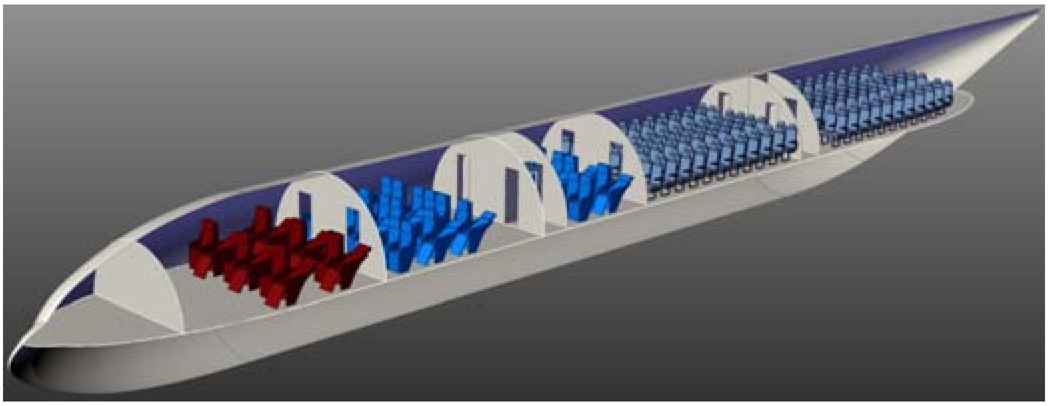


Figure A-7 3-D Arrangement for Medium-range Baseline

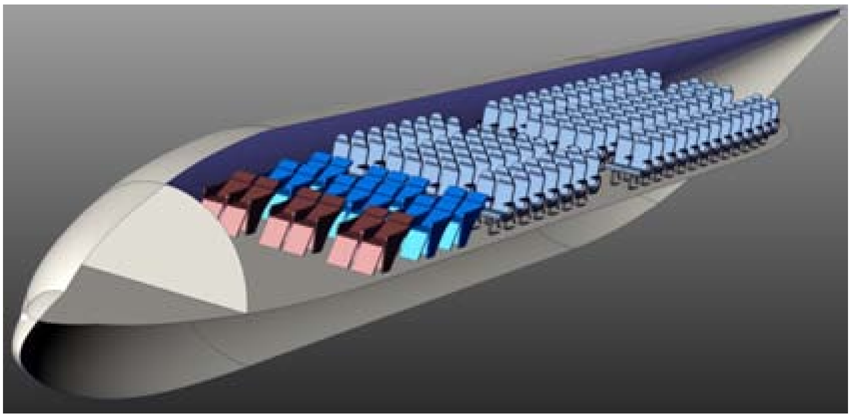


Figure A-8 3-D Arrangement for Long-range Baseline

A.4.3 Cabin layout of FW-11

A.4.3.1 General 2-D cabin arrangement

The figure below shows the general configuration of FW-11. This final configuration is a compromise result of aerodynamic, mass & CG, structure, landing gears, engine installation, performance and cabin layout.

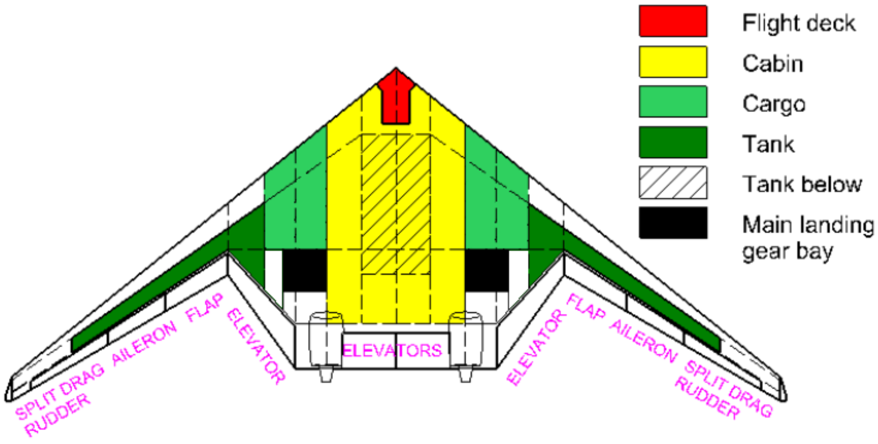


Figure A-9 FW-11 Configuration [45]

Then, based on this general configuration and requirement from design phase I, the 2-D definition of cabin is shown as below.

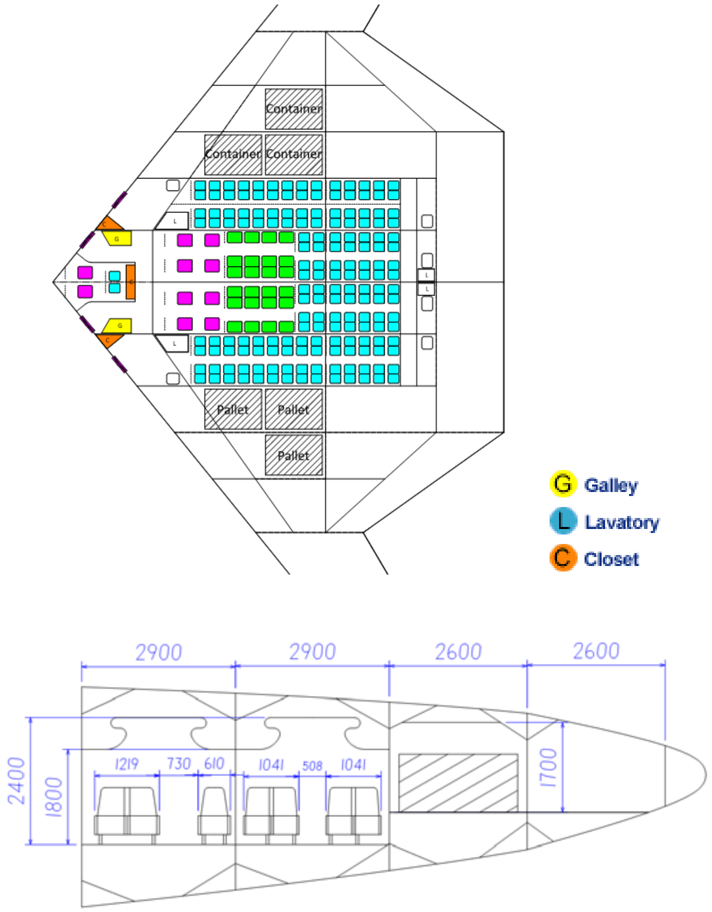


Figure A-10 FW-11 2-D Cabin Layout and Cross Section

A.4.3.2 3-D Cabin Arrangement, Simulation and Virtual Reality

Cabin arrangement is more difficult in 3-D environment, many issues are found when structure, landing gears, seats, cargos, doors and emergency exits get together.

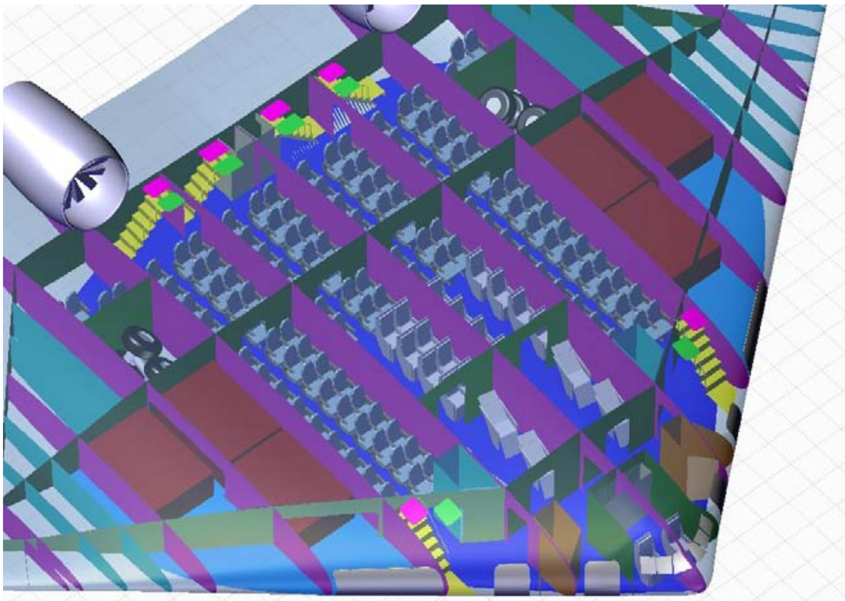


Figure A-11 FW-11 3-D Cabin Arrangement

In the final configuration, parts of the leading edge are used as cargo doors. To evaluate the feasibility of this idea, a simple cargo loading and unloading simulation is done by the author.

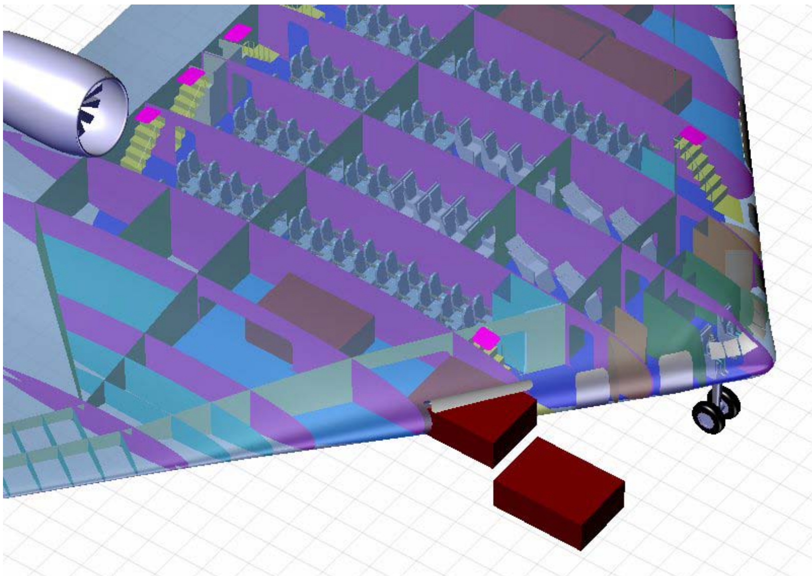


Figure A-12 Cargo Unloading Simulation

To evaluate the passenger comfort in the cabin, virtual reality (VR) method is introduced.

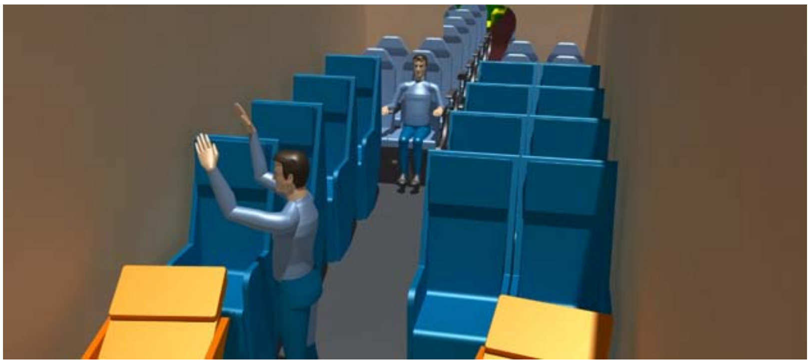


Figure A-13 Passenger Comfort VR

Although FW-11 cabin layout aims to meet a more passenger comfort than Airbus A380 and Boeing 787, due to the stress and manufacturing constrains, FW-11 structure layout use Y-braced Integrated Box solution which makes the cabin area divided into four individual bays. The VR result indicates that each bay is a narrow body airliner type (2-2 seat configuration) cabin. In additional, no windows can be designed in cabin area. If passengers are in the three classes mixed cabin, they will feel staying in small boxes. In order to ease the impact of narrow body, advance entertainment system is proposed. However, the design of economy seat pitch and width has its advantage of sitting comfort. With the application of virtual environment technology, the windows problem is not a passenger concern. Considered a further development in next five years, the passenger comfort of FW-11 is at least in the same level as Boeing 787.

A.4.3.3 Challenges in Flying Wing Cabin Layout

Because the aerodynamics efficiency is the most important factor in flying wing concept aircraft design, each section cut from heading direction should be an airfoil shape. This design constraint leads to the difficulty of cabin design especially for the cabin and cargo height. In quite a long time, the available height for cabin and cargo is not enough. Since the minimal cabin height is only 1.8 meters before, there is no space for the rack on that position. For the cargo design, the initial idea is arrange standard containers in rear cabin area, but a further design from other group found the wing span is too long to fit airports. The author had to change the cargo position to two sides of the inner wing, and adjust standard containers to non-standard container (dimension: 88 in (width) × 125 in (length) × 43 in (height)) or standard pallets with limited height (88 in (width) × 125 in (length) × 42 in (height)).

What is more, the conflict with landing gears position, CG, engine installation and aerodynamics efficiency once made the cabin design changing frequently. For example, the emergency exits were located in other position which is better for evacuation on the surface. Due to the engine installation position and type change, two emergency exits were adjusted to avoid passenger involved into dangerous engine area.

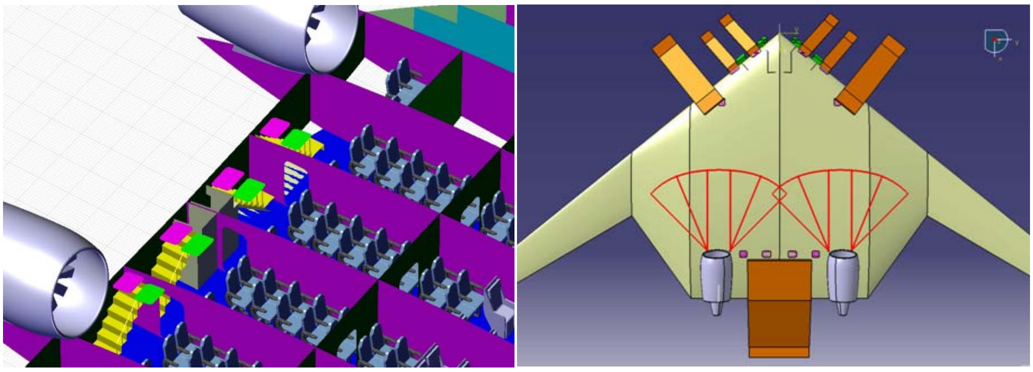


Figure A-14 FW-11 Evacuation

A.4.4 Issues of Flying Wing Family Development Strategy

The family development of FW-11 is partly related to the author's IRP. As early as in the late of design phase II, Blended Wing Body (BWB), delta wing and flying wing were compared in aspects. At that time, research had been taken place on BWB family development firstly.

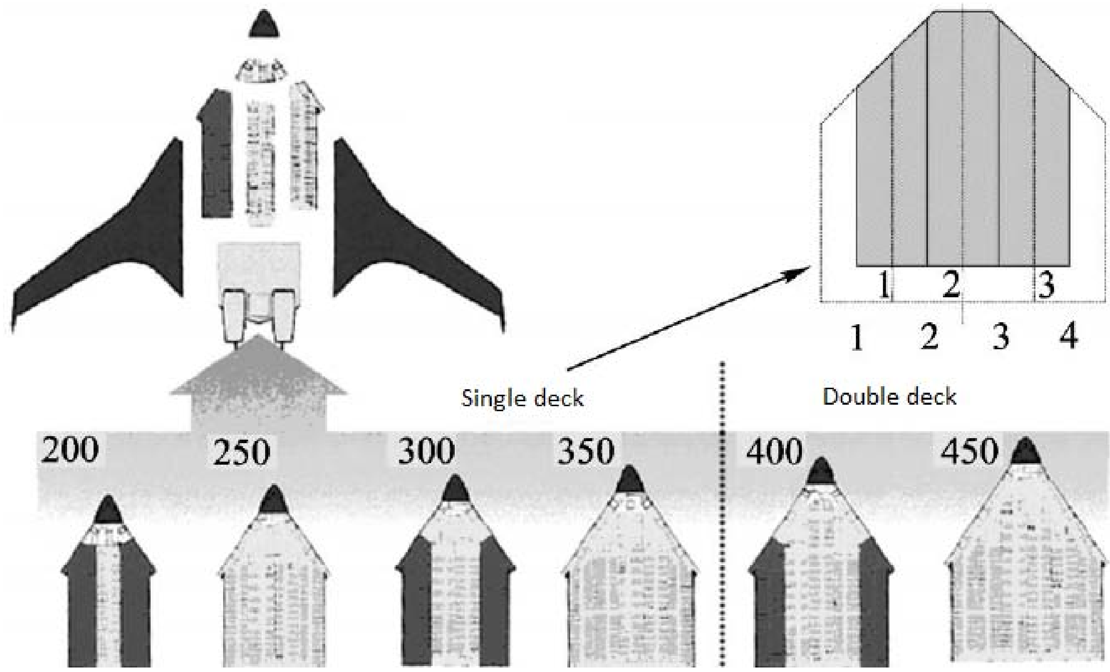


Figure A-15 BWB Aircraft Family Development [50]

The idea for BWB family development is to share the same wing and change the fuselage dimensions to meet passengers increasing. In spite of the landing gears' type and location problem, this strategy is feasible. Because the main advantage of BWB is more aerodynamic efficiency than conventional aircrafts. Compared with the main lift body - wings, fuselage becomes a semi-lift body. The changes of fuselage dimensions affect little to the aerodynamic efficiency and performance. But for flying wing aircraft, it is more efficient than BWB, because the whole aircraft is a good lift body and each section cut from heading direction is an airfoil shape. The FW-11 cabin and cargo area are defined as the inner wing. Since the aerodynamics of flying wing is sensitive for geometry, simply changes of the inner wing will lead to a significant effect to aerodynamic efficiency. As a reason of that, this development strategy is difficult for flying wing aircrafts.

With a integrated point of view concluding factors like aerodynamics, performance, manufacturing and cost, the family development strategy proposed by the author is to base on a typical aircraft, then use flexible seats and cargo configuration to meet the passenger number change first; then consider changing the width of inner wing to add more bays. The principle for inner and outer wing changes is to balance the aerodynamics, performance, manufacturing and cost. It is much more difficult to develop family issue for flying wing aircraft than conventional and BWB aircrafts. The idea of develop a family issue is to meet the rapid growing market requirement and reduce the new product development cycle. So for flying wing approach, this question comes back to the initial design drive which is the market. A further market prediction is essential for the family issue development.

A.4.5 Presentation Video Produce Introduction

In the last two weeks, the author was in charge of the video produce for final presentation. This is a time consuming work due to lots of GDP work need to be presented in limited times. A brief introduction of the produce process will be given. The software used for the task are all educational edition or in their free trial period

The video produce is based on the final CAD data in FW-11 conceptual design including cabin layout, general geometry, structure, landing gears, nacelle and engine. The author assembly them in DASSAULT SYSTEMES CATIA firstly, then import the product data into DASSAULT SYSTEMES 3DVIA Composer which is a 3-D technical illustration software. After that, many short clips are made according to define the key frame of CAD data elements and video output function. At last, clips are produced in the video editing software CyberLink Power Director.

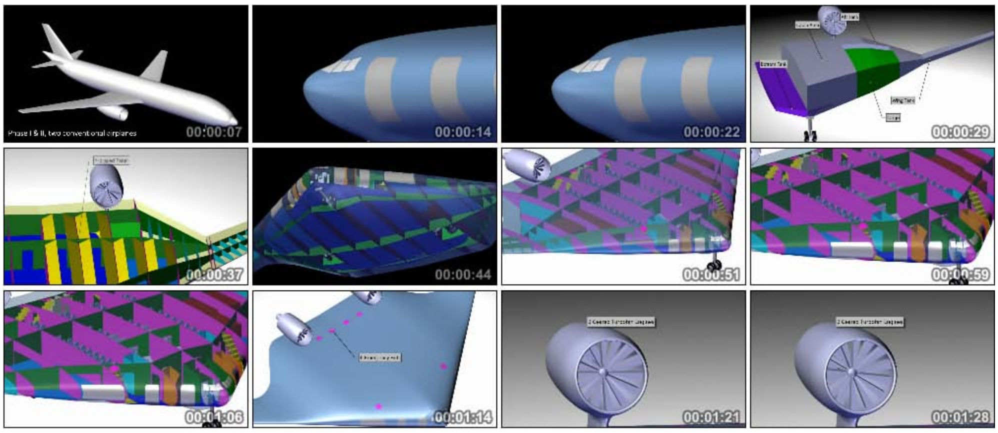


Figure A-16 FW-11 Final Presentation Video

Appendix B System Assembly Process Planning in Text Mode

This part will illustrate the system assembly process planning in text mode. The Flying Crane wing fuel system is used as the sample.

B.1 Title of Assembly Plan

Installation of Right Wing Fuel System Tubes

B.2 Operation Instructions

B.2.1 Work Description

- This assembly plan applicable to the installation of right wing fuel system tubes.
- Compilation reference of this plan is the drawing of Flying Crane fuel system.
- Get familiar with and master related process procedure before working on this plan.

B.2.2 Work Content

Step 1: Receive the tubes from the ware house. Check the appearance quality and verify the parts & certificates.

Step 2: Install Tube001 between rib FC-0420-006-R and FC-0420-007-R. Locate Tube001 using Buckle001 at Support001 which is on rib FC-0420-007-R.

Tube001 1pc
Buckle001 1pc
Bolt type1_16_4 1pc

Step 3: Install Tube002 between rib FC-0420-005-R and FC-0420-006-R. Locate Tube002 using Buckle001 at Support001 which is on rib FC-0420-006-R. Butt joint Tube002 with Tube001.

Tube002 1pc
Buckle001 1pc

Bolt type1_16_4 1pc

Step 4: Install Tube003 between rib FC-0420-004-R and FC-0420-005-R. Locate Tube003 using Buckle001 at Support001 which is on rib FC-0420-005-R. Butt joint Tube003 with Tube002 and two fuel pumps.

Tube003 1pc

Buckle001 1pc

Bolt type1_16_4 1pc

Step 5: Install Tube004 between rib FC-0420-003-R and FC-0420-004-R. Locate Tube004 using two Buckle001s at Support001s which are on rib FC-0420-003-R and FC-0420-004-R. Butt joint Tube004 with Tube003.

Tube004 1pc

Buckle001 2pc

Bolt type1_16_4 2pc

Step 6: Install Tube005 between rib FC-0420-001-R and FC-0420-003-R. Butt joint Tube005 with Tube004.

Tube005 1pc

Step 7: Clean the work site, check the part and tool.

Step 8: Inspection. Check the appearance quality of tube. Ensure the correct installation and reliable fixation and safety.

B.2.3 Figure

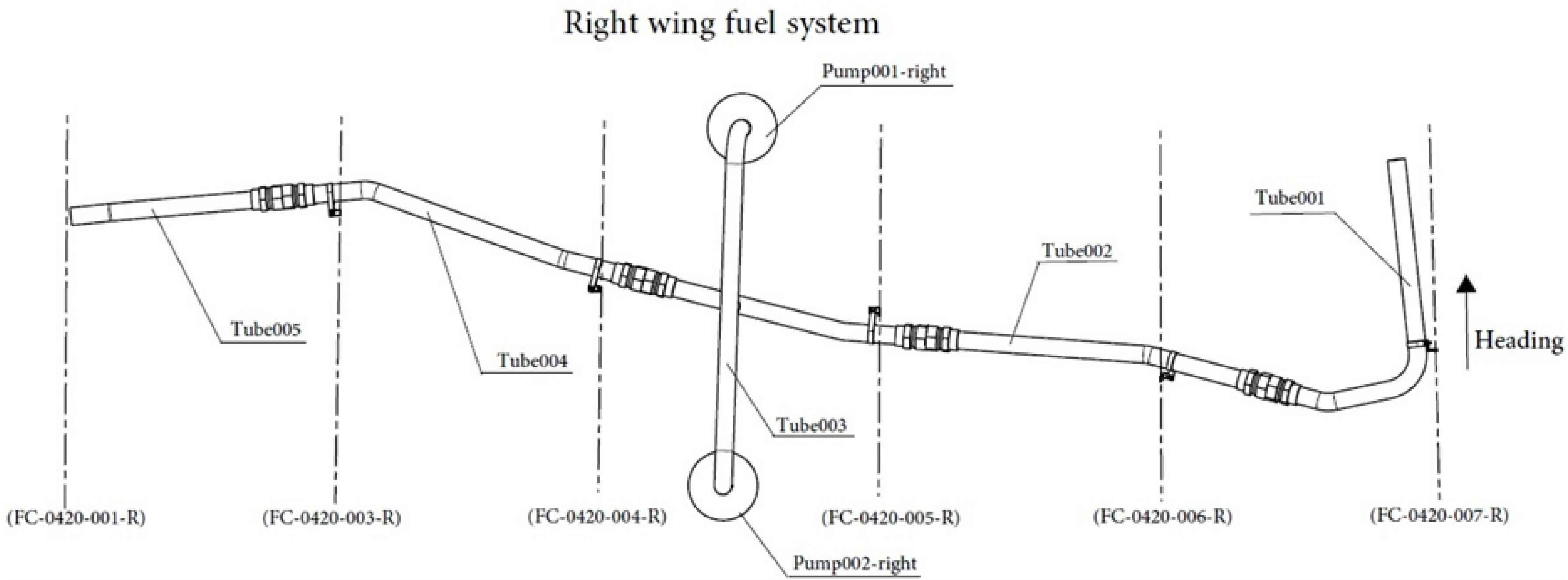


Figure B-1 Installation of Right Wing Fuel System

B.3 Parts and Material Required

Table B-1 Parts Required

SEQ.	PART NO	PART NAME	QTY.	PROCESS ROUTE	NOTES	NEXT ASSY.	QLY. CD.
1	Tube001	Tube	1			FC	
2	Tube002	Tube	1			FC	
3	Tube003	Tube	1			FC	
4	Tube004	Tube	1			FC	
5	Tube005	Tube	1			FC	
6	Buckle001	Bracket	5			FC	

Table B-2 Standard Parts & Material Required

SEQ.	NUMBER	NAME	QTY.	NEXT ASSY.	NOTES
1	Type1_16_4	Bolt	5	FC	

B.4 Shipset Record

Table B-3 Shipset Record

NO.	STAMP/DATE	DISCREPANCY	OPERATION	INSP.STAMP

B.5 Drawing and Change Required

Table B-4 Drawing and Change Required

DRAWING.	DRAWING CHANGE SHEET NO.		
FC			

B.6 Summary of Change

Table B-5 Summary of Change

REV.	DATA	SUMMARY OF CHANGE	PLANNER	VERIFY	INSP.
00		Initial plan			

Appendix C Case Study 1 Detailed Modelling and Simulation

C.1 Flying Crane Fuel System Modelling

C.1.1 Define the Hierarchical Product Structure

The first step for creating an assembly model is to decide on a logical structure for the model.

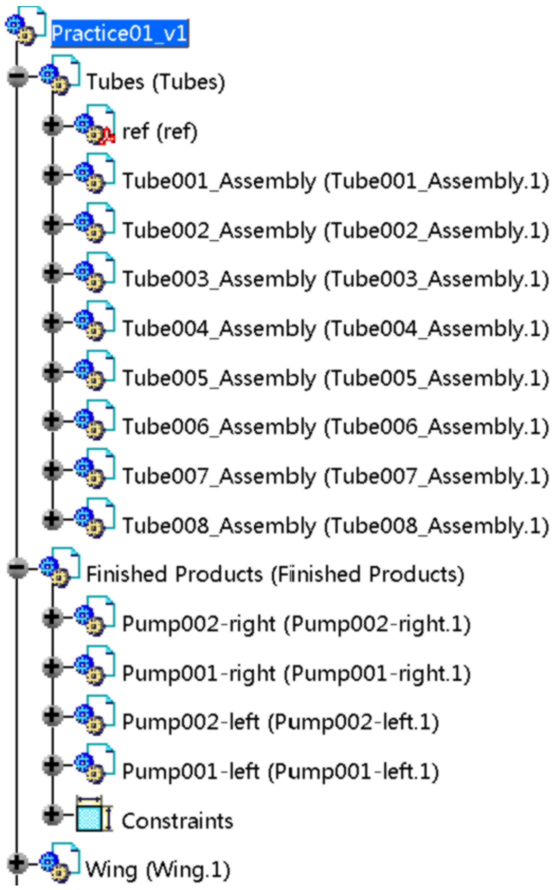


Figure C-1 Logical Structure of the Flying Crane Fuel System Model

C.1.2 Add the Reference Points

Reference points are designed to help the further tube modelling. Compass and measure tools can be used to obtain the coordinates of points. Reference points are then defined in CATIA part design module.

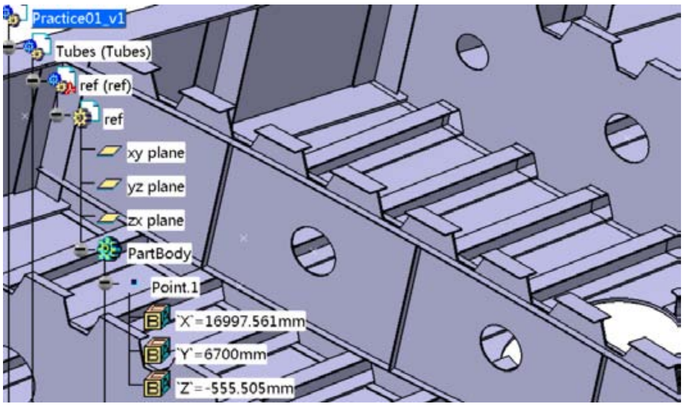


Figure C-2 Definition of Reference Points

C.1.3 Tubing Modelling

Enter Tubing Discipline module and use Tubing Design tool to create the tubing runs.

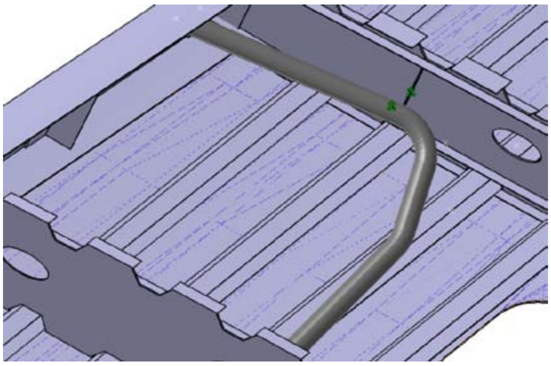


Figure C-3 Route the Run

Runs can be edited by right clicking and choosing the Runxxx.object – Definition in the contextual menu.

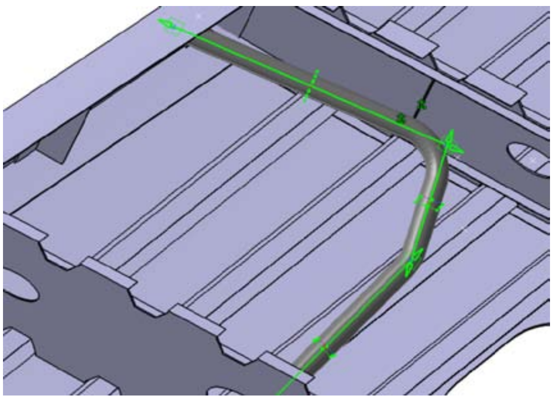


Figure C-4 Modifying the Run

After that, parts can be placed on a run.

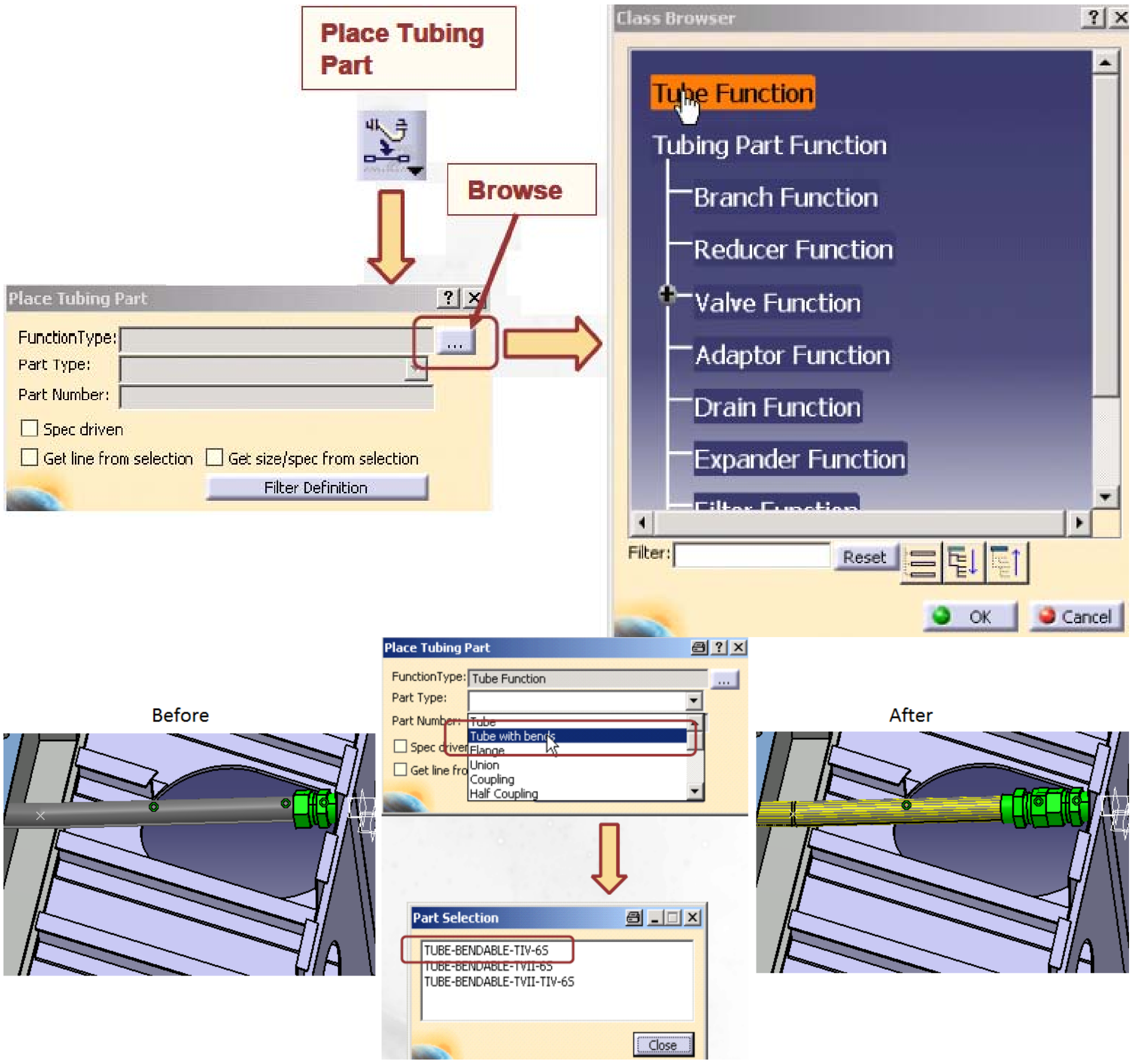


Figure C-5 Place Tubing Part

C.1.4 Application of DFA Principles

Followed by the DFA principles of accessible, visible and parts reduction requirement, all the supports and brackets are considered using the same geometry to decrease the number of parts. The separation of fuel pipes also follows this principle.

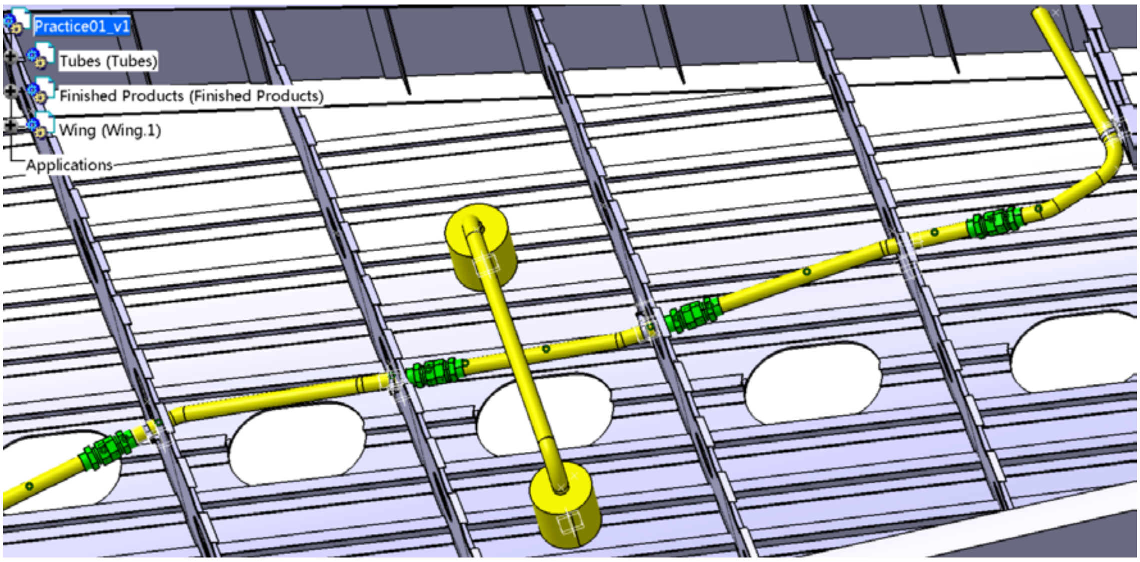


Figure C-6 Separation of Fuel Pipes

C.2 Assembly Simulation in 3DVIA System

C.2.1 Application of 3DVIA License

Full function free trial license can apply on the official website of 3DVIA. The request form can be found on http://www.3dviacomposer.com/try/request.php.

After fill the form, a downlink will be sent to the registered mail address. The free trial license will be automatic installed when finishing the setup of 3DVIA. 3DVIA Player tool should be manually registered the license.

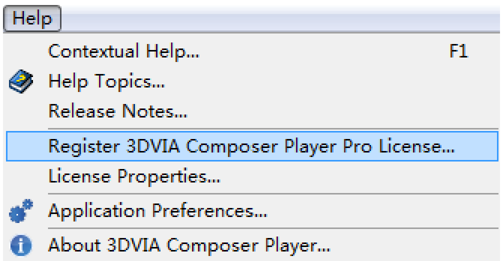


Figure C-7 License Installation

C.2.2 Simulation Process

The first step is importing raw CATIA assembly design data to 3DVIA lightweight data.

Open 3DVIA sync tool, the importing operations are shown as below.

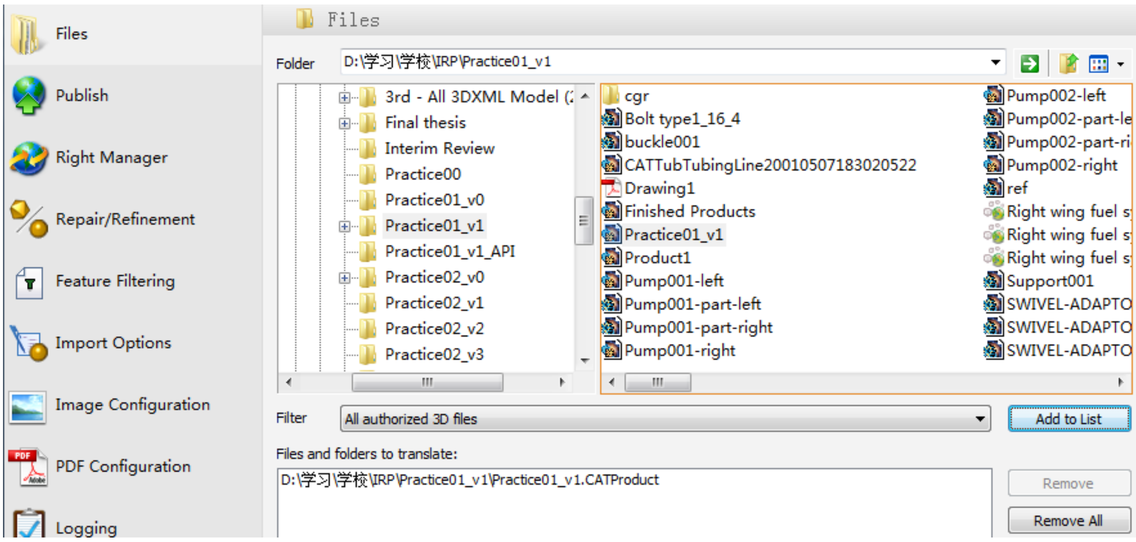


Figure C-8 Location of the CATIA Assembly File

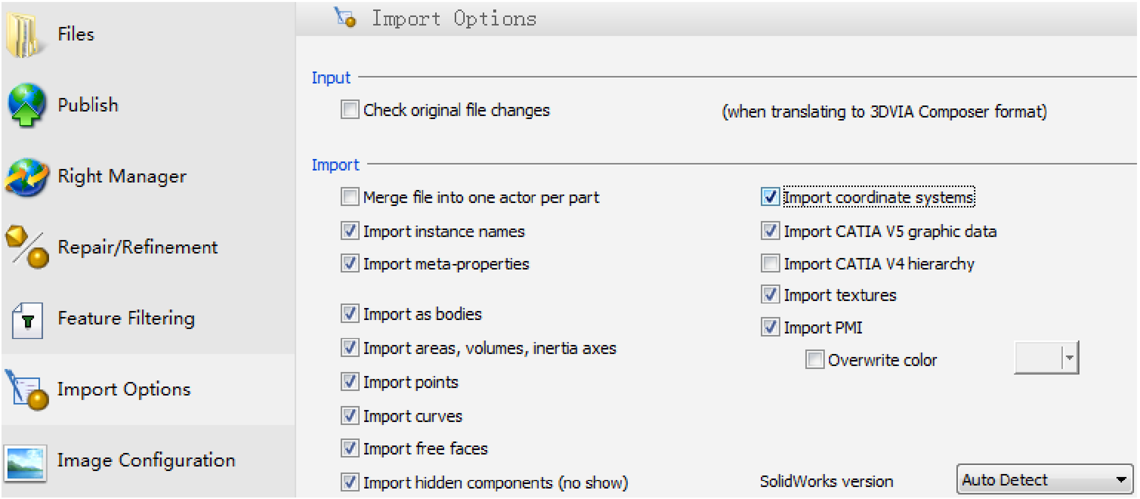


Figure C-9 Importing Options

The 3DVIA sync tool will output the lightweight CAD data in smg format.

3DVIA Composer uses a key frame-based interface built into a timeline. The timeline pane allows easy access to keys, filters, and playback tools, simplifying the creation and editing processes.

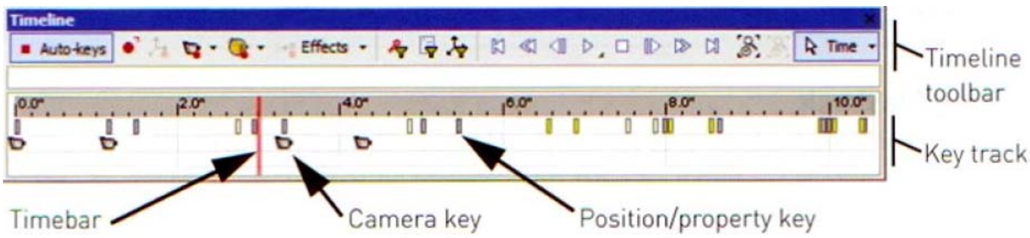


Figure C-10 Timeline Pane

The following figures illustrate the basic assembly simulation operations. Advanced operation refers to Appendix D.

- Adjust the model to certain position, and then set the initial camera key to fit the view.

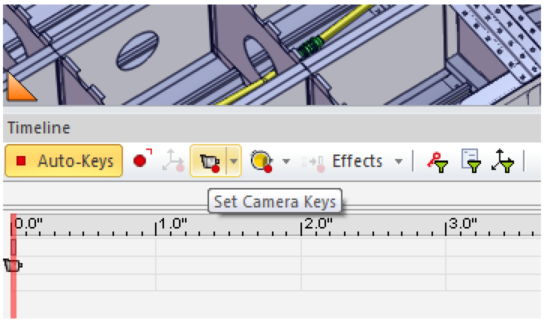


Figure C-11 Set Camera Key

- Move the timebar to 2 second, adjust the position again. Set another camera key.
- Move the timebar to 2.2 second. Select the pipe end style by clicking it. Set a location (position) key.

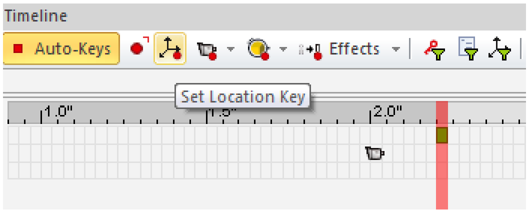


Figure C-12 Set Location Key

- Move the timebar to 3 second. Keep the selection the pipe end style. Choose the translation mode in right clicking menu. Drag the pivot to move the connector of end style. Then set another location (position) key.

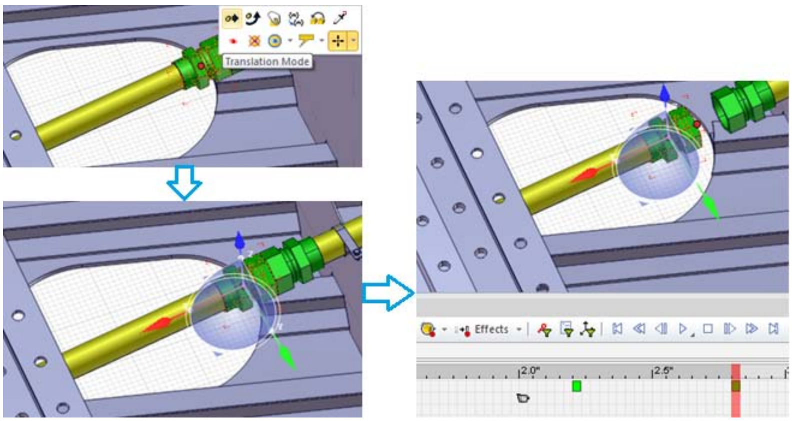


Figure C-13 Basic Operation of Simulation

- Select the whole pipe in the assembly tree. Use translation and rotation mode interchangeably from the right clicking menu, and then define the location keys respectively to produce the simulation. The pipes are simulated the disassembly process with this method.
- Select the author tool from the ribbon toolbar and click 2-D text or label icon to create assembly notations and parts feeding instructions. It should be noticed that all these operation must be defined with keys in timeline.

Thus, a complete key definition of Flying Crane assembly simulation is shown as below.

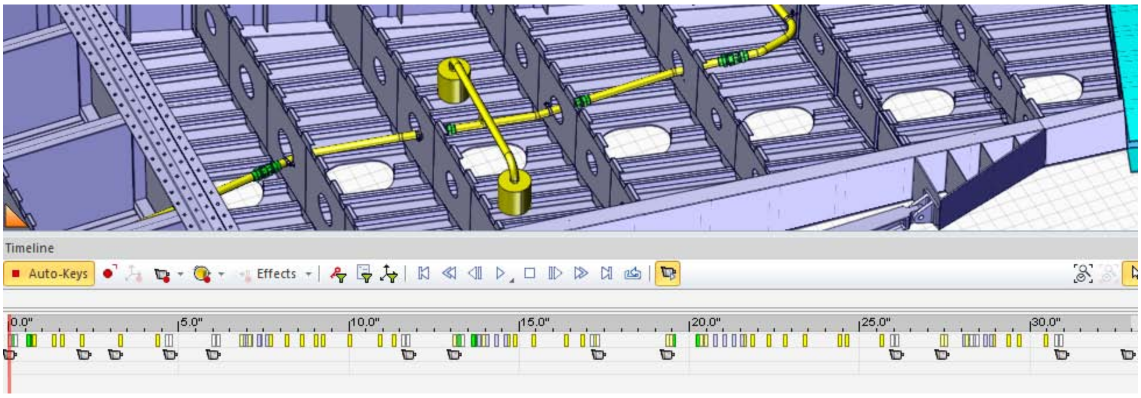


Figure C-14 Key Definition of Flying Crane Assembly Simulation

Appendix D Case Study 2 Detailed Modelling and Simulation

This part introduces the detailed modelling and simulation of AVD A-8 case. Since basic system modelling and assembly simulation operations have been described in Appendix C, this part will only concentrate on some advance operations.

D.1 ECS Pipe Modelling

There are two methods for pipe modelling. The first method is Tubing Design tool in Tubing Discipline module which has been introduced in Appendix C. The other one is use Wireframe and Surface design tool and Part design tool. The following steps will illustrate the second one.

- Define the reference points using the method introduced in Appendix C.
- Enter Wireframe and Surface design environment and design the pipe central line and end style circle.
- Then use sweep tool to obtain the surface.

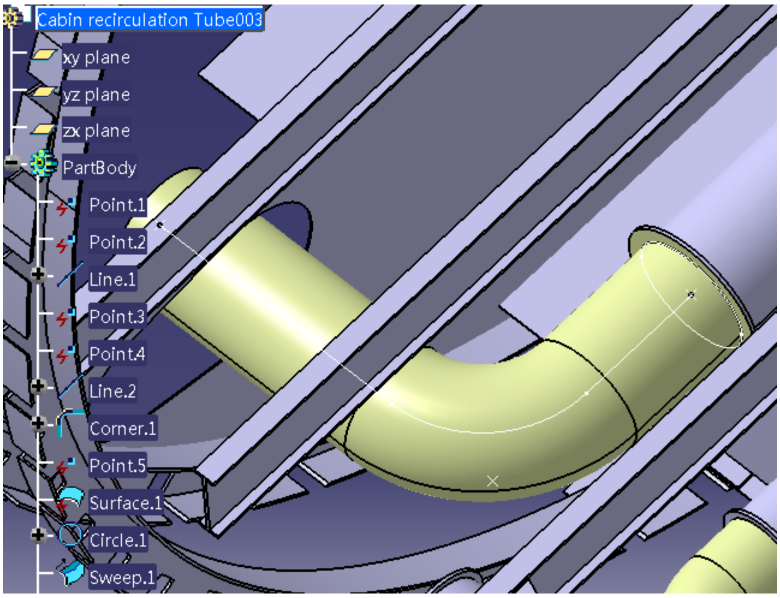


Figure D-1 Pipe Modelling in Wireframe and Surface Design Environment

- Enter Part design environment, define the thick surface to build the pipe solid surface. Then use pad tool to design the pipe end style.

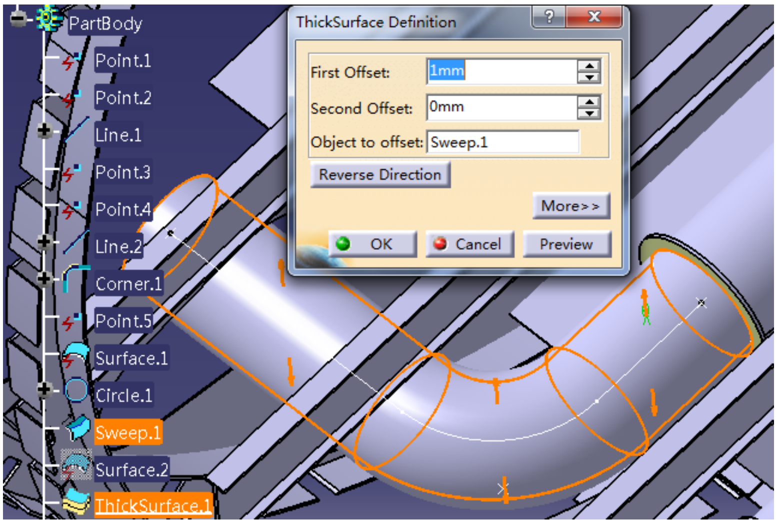


Figure D-2 Pipe Modelling in Part Design Environment

D.2 Application of DFA Principles in System Modelling

Some DFA principles are followed for modelling which are listed below.

- If possible, the pipe brackets are designed as the same when pipes have the same diameter to reduce parts number.

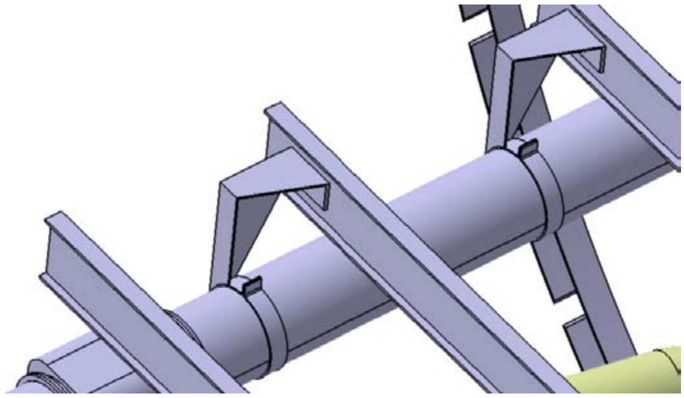


Figure D-3 Pipe Brackets Design

- The supports of ECS packs are designed with the same geometry since some ECS packs are the same to reduce parts number.

- Because ECS packs are designed to install through the access panel on the floor, the accessibility is poor in this way. To solve the problem, the installation way is design as insertion. The principles of eliminating adjustments and self-aligning (location) are applied in this case.

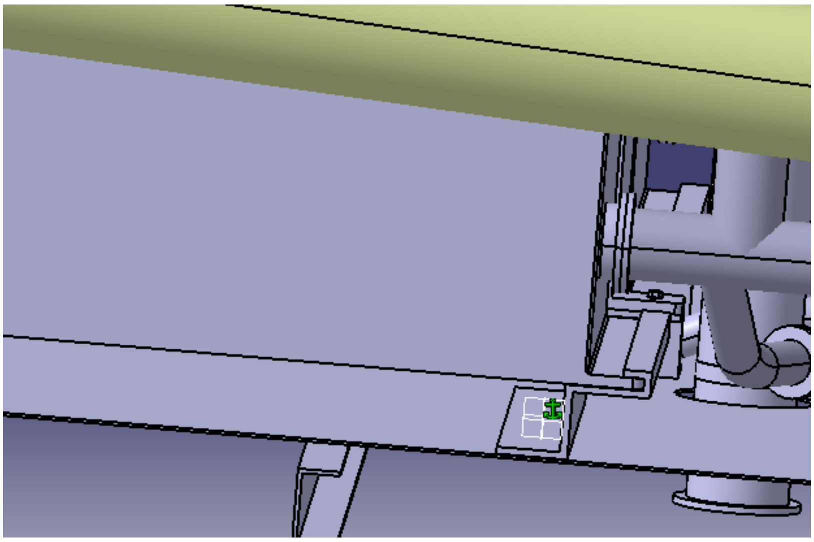


Figure D-4 Installation Way of ECS Packs

- Fasteners are also designed to ease the assembly. Washers are designed as a part of the bolt to meet the principle of parts reduction, while nuts are involved in supports as self-locking nuts to fit the principles of preventing improper installation, ease of handling and eliminating adjustments.

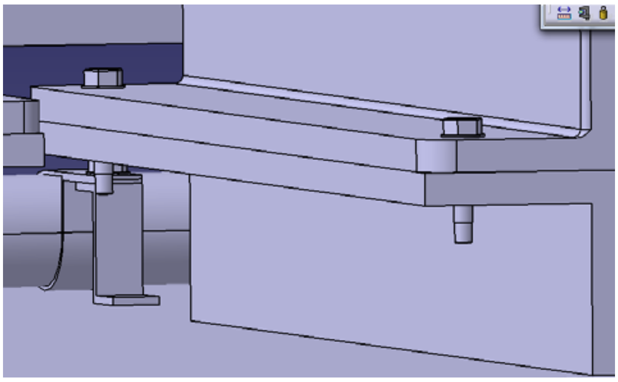


Figure D-5 Fastener Design of ECS Packs

- Two pipe brackets are designed to share one fastener to meet the principles of parts reduction.

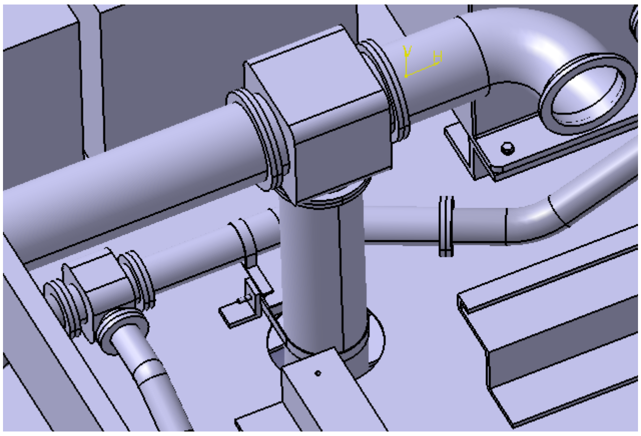


Figure D-6 Two Pipe Brackets Share One Fastener

D.3 Assembly Simulation in 3DVIA System

In complicated assembly environment, it is hard to manipulate parts with some actions. An advanced operation used for this situation is introduced below.

- Select the pipe by clicking it on the geometry or assembly tree.
- Choose rotation mode in the right clicking menu.
- Long press Alt on the keyboard to capture the reference of rotation. The reference will become red colour.

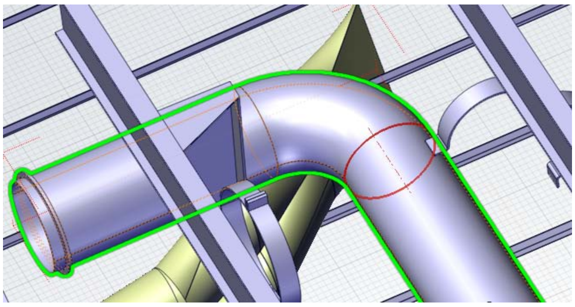


Figure D-7 Reference of Rotation

- Select the needed reference by clicking it. Then the pipe can be manipulated with customized reference.

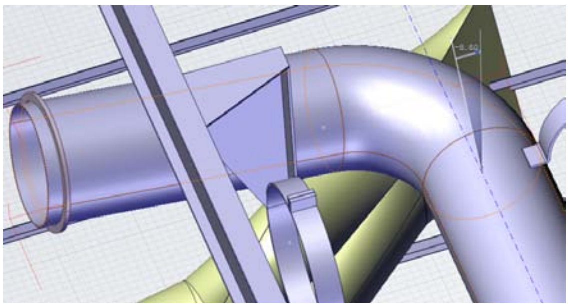


Figure D-8 Customized Rotation Manipulation

Thus, the simulation operation becomes more flexible in this way. The figure below shows the moving path in red lines of this pipe.

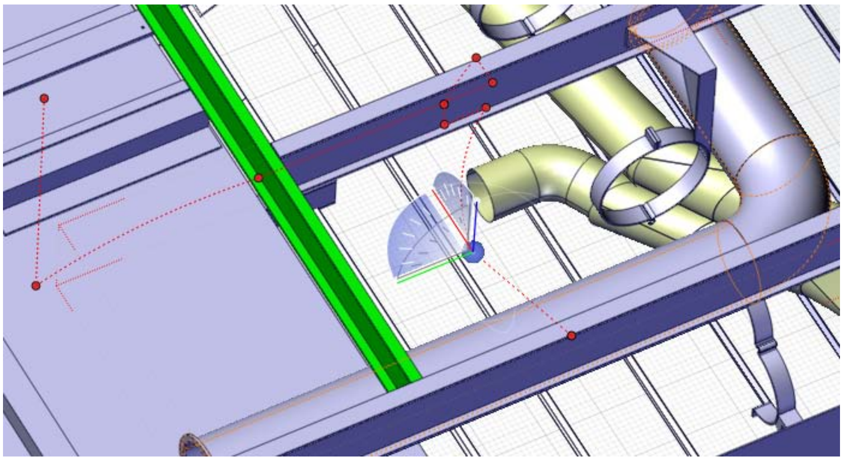


Figure D-9 Moving Path of Pipe

The picture below shows the finished key definition of A-8 ECS assembly simulation in the ECS bay.

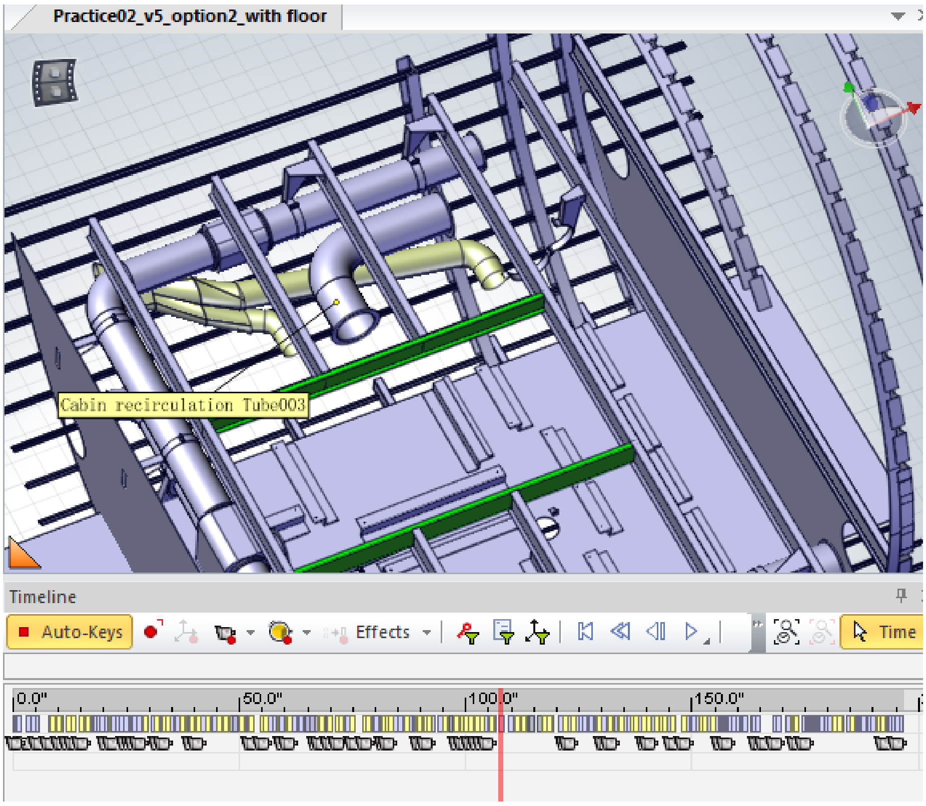


Figure D-10 Key Definition of A-8 ECS Assembly Simulation

Appendix E Assembly Instruction Produce and Secondary Development

E.1 Assembly Instruction Produce

When finishing the assembly simulation with key definition in 3DVIA, two types of assembly instruction can be produced.

The first type is output to AVI video file. The operation is listed as below.

- Select video workshop from the ribbon bar.
- Select “Change windows resolution” and input the needed resolution for output video. Set the anti-aliasing options if needed.
- Click “Save video as” to output assembly movie.
- Reverse the recorded disassembly video to assembly order in video editing application.

The second type is output interactive 3-D assembly instructions. It should be noticed that when opening smg files in 3DVIA Player tool, the environment is interactive. The following steps will show the operations when 3DVIA system is not installed in end users’ computer.

- Select File in the ribbon bar, and click save as package.
- Set security and right manager options if needed.
- Click “Save” to output executable package. Then this package can be used in the computer which does not have 3DVIA installed.

E.2 Integration with ActiveX Support Application

E.2.1 Define Customized Views and Markers

Customized views are used to present particular concerns to end user, while markers are used to mark certain position in the timeline. In the assembly instruction, markers are treated as the definition of subassemblies. The figure below shows the definition of views and markers.

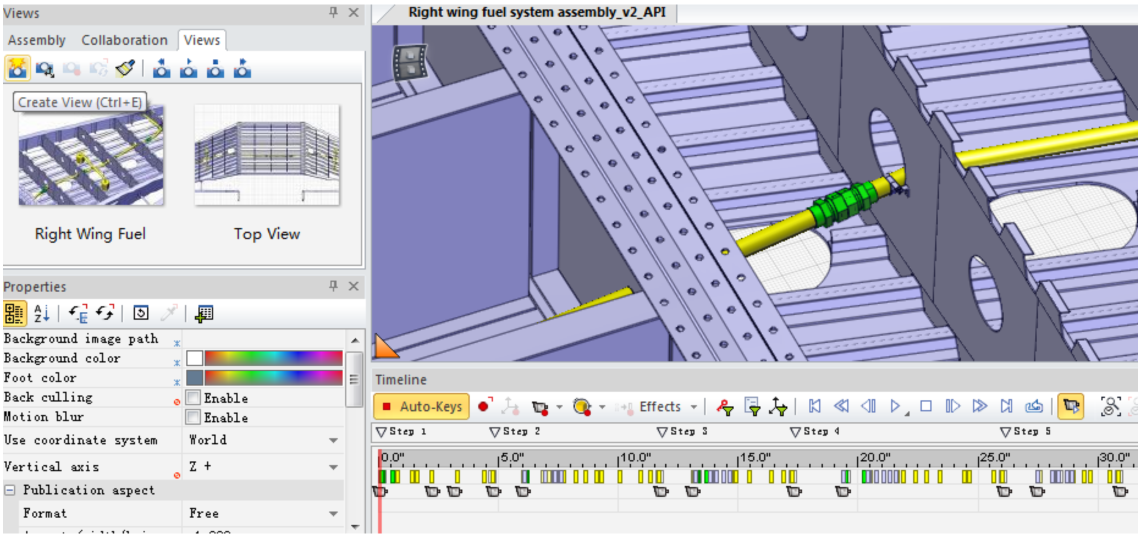


Figure E-1 Definition of Views and Markers

E.2.2 Integration Process

This part will use Flying Crane as an example to integrate the lightweight CAD data into Microsoft Office PowerPoint which supports ActiveX.

- Create a slide that has only a box for the title. Input title name if needed.
- In PowerPoint 2007, click PowerPoint Options and select Show Developer tab in the Ribbon. On the Developer tab, click More Controls.
- Drag a rectangle across the slide to add the control. Make it big because this is where 3DVIA Player displays the file.
- Right-click the control and select 3DVIAPlayerActiveXControlObject. Properties. Locate the saved smg file and set the general tab.

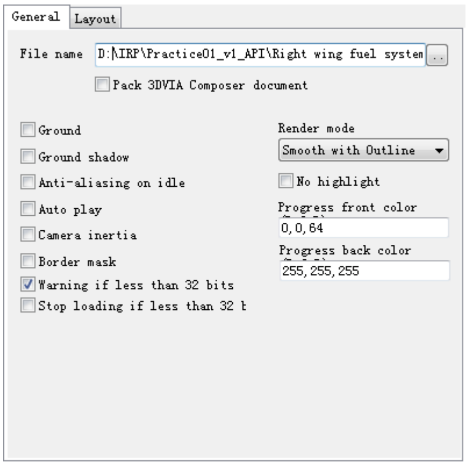


Figure E-2 Set the General Tab

- Drag another rectangle from the Developer tab across the slide to add the control. Right-click it and select property then input name and caption value.

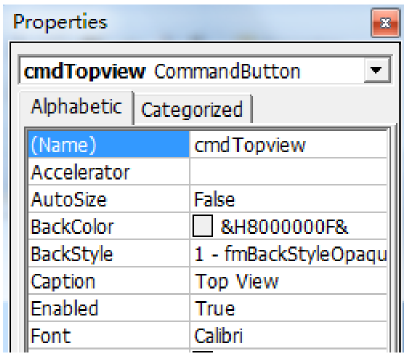


Figure E-3 Change Property of Control

- Double-click the control button to enter Microsoft Visual Basic dialog box. Then type the following between Private Sub and End Sub lines: DS3DVIAPlayerActiveX1.GoToConfiguration ("Top View")
- Add other control icons as the process described before.

E.3 VBA Programming Codes

A finished customized application is illustrated in figure 5-8. The VBA programming codes are shown as below.

```
Dim InversePause As Boolean
Dim InverseStop As Boolean
Dim InversePlay As Boolean

Private Sub Camera_Click()
If Camera = True Then DS3DVIAPlayerActiveX1.CameraPlayMode = True Else
DS3DVIAPlayerActiveX1.CameraPlayMode = False
End Sub

Private Sub cmd1_Click()
   If optForward.Value = True Then
      DS3DVIAPlayerActiveX1.PlayMarkerSequence ("Step 1")
   ElseIf optBackward.Value = True Then
      PlayMarkerSequenceInverse ("Step 6")
   Else
      Exit Sub
   End If
End Sub

Private Sub cmd2_Click()
```

```
    If optForward.Value = True Then
        DS3DVIAPlayerActiveX1.PlayMarkerSequence ("Step 2")
    ElseIf optBackward.Value = True Then
        PlayMarkerSequenceInverse ("Step 5")
    Else
        Exit Sub
    End If
End Sub

Private Sub cmd3_Click()
    If optForward.Value = True Then
        DS3DVIAPlayerActiveX1.PlayMarkerSequence ("Step 3")
    ElseIf optBackward.Value = True Then
        PlayMarkerSequenceInverse ("Step 4")
    Else
        Exit Sub
    End If
End Sub

Private Sub cmd4_Click()
    If optForward.Value = True Then
        DS3DVIAPlayerActiveX1.PlayMarkerSequence ("Step 4")
    ElseIf optBackward.Value = True Then
        PlayMarkerSequenceInverse ("Step 3")
    Else
        Exit Sub
    End If
End Sub

Private Sub cmd5_Click()
    If optForward.Value = True Then
        DS3DVIAPlayerActiveX1.PlayMarkerSequence ("Step 5")
    ElseIf optBackward.Value = True Then
        PlayMarkerSequenceInverse ("Step 2")
    Else
        Exit Sub
    End If
End Sub

Private Sub cmdStop_Click()
    If optForward.Value = True Then
        InverseStop = False
        DS3DVIAPlayerActiveX1.Stop
    ElseIf optBackward.Value = True Then
        InverseStop = True
    Else
        Exit Sub
    End If
```

```
End Sub
Private Sub cmdPlay_Click()
   If optForward.Value = True Then
      InversePlay = False
      DS3DVIAPlayerActiveX1.Play
   ElseIf optBackward.Value = True Then
      InversePlay = True
   Else
      Exit Sub
   End If
End Sub

Private Sub cmdPause_Click()
   Static bPause As Boolean
   If optForward.Value = True Then
      DS3DVIAPlayerActiveX1.Pause
   ElseIf optBackward.Value = True Then
      If bPause = False Then
         InversePause = True
         bPause = True
      ElseIf bPause = True Then
         InversePause = False
         bPause = False
      End If
   End If
End Sub

Private Sub PlayMarkerSequenceInverse(markerName As String)

   On Error GoTo here
   Dim str, strMarker As String
   Dim nIndex, nMarkerBegin, nMarkerEnd, nPos As Integer
   DS3DVIAPlayerActiveX1.GoToMarker ("Step 1")
   str = DS3DVIAPlayerActiveX1.GetAllMarkers

   nIndex = InStr(1, str, markerName)
      nMarkerEnd = InStrRev(str, "/", nIndex, 1) - 1
      If nMarkerEnd <= 0 Then
         MsgBox "you have already reached the first step"
         Exit Sub
      Else
         nMarkerBegin = InStrRev(str, "CLitModifiable Name=", nMarkerEnd, 1) +
21
         strMarker = Mid(str, nMarkerBegin, nMarkerEnd - nMarkerBegin)
         If DS3DVIAPlayerActiveX1.GoToMarker(strMarker) = False Then
            Exit Sub
         Else
           nPos = DS3DVIAPlayerActiveX1.Pos
```

```
        End If
          DS3DVIAPlayerActiveX1.GoToMarker (markerName)

        Do While (DS3DVIAPlayerActiveX1.Pos > 0)
           If (DS3DVIAPlayerActiveX1.Pos > nPos) Then
              If (InversePause = True) Then
                 DS3DVIAPlayerActiveX1.Pause
                 GoTo here
              ElseIf (InversePause = False) Then
                 DS3DVIAPlayerActiveX1.Pos = DS3DVIAPlayerActiveX1.Pos - 1
              End If
           End If

           If InverseStop = True Then
              DS3DVIAPlayerActiveX1.Stop
              GoTo here
           End If

           If InversePlay = True Then
              DS3DVIAPlayerActiveX1.Pos = DS3DVIAPlayerActiveX1.Pos - 1
           End If

           DoEvents
        Loop
     End If
here:
   InversePause = False
   InverseStop = False
   InversePlay = False
End Sub

Private Sub cmdTopview_Click()
   DS3DVIAPlayerActiveX1.GoToConfiguration ("Top View")
End Sub

Private Sub cmdDetailview_Click()
   DS3DVIAPlayerActiveX1.GoToConfiguration ("Right Wing Fuel")
End Sub

Private Sub DS3DVIAPlayerActiveX1_ReadyStateChange()

End Sub

Private Sub Measurement_Click()
   If Measurement = True Then
      DS3DVIAPlayerActiveX1.ShowMeasurementToolBar = True
   Else
      DS3DVIAPlayerActiveX1.ShowMeasurementToolBar = False
```

```
    End If
End Sub

Private Sub Timebar_Click()
    If Timebar = True Then
        DS3DVIAPlayerActiveX1.ShowTimelineBar = True
    Else
        DS3DVIAPlayerActiveX1.ShowTimelineBar = False
    End If
End Sub

Private Sub Toolbar_Click()
    If Toolbar = True Then
        DS3DVIAPlayerActiveX1.ShowStandardToolBar = True
    Else
        DS3DVIAPlayerActiveX1.ShowStandardToolBar = False
    End If
End Sub

Private Sub Tree_Click()
    If Tree = True Then
        DS3DVIAPlayerActiveX1.ShowAssemblyTreeBar = True
    Else
        DS3DVIAPlayerActiveX1.ShowAssemblyTreeBar = False
    End If
End Sub
```